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The circular economy and the bioeconomy

Partners in sustainability

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Executive summary

Objective and scope

This is the third in a series of European Environment Agency (EEA) reports on the circular economy in support of the framing, implementation and evaluation of European circular economy policy from an environmental perspective. The two previous EEA reports applied a systemic approach to framing a circular economy (EEA, 2016) and to the products within it (EEA, 2017a). This report on the bioeconomy ([1]) addresses circularity aspects of bio-based products and the sustainable use of renewable natural resources.

The concepts of both the bioeconomy and the circular economy have been introduced in the European Union (EU) in response to concerns about the long-term viability of the prevailing resource-intensive economic model. Although different in origin — the first mostly driven by an innovation agenda and the second by environmental concerns and resource scarcity — both aim to contribute to strategic and operational EU policy objectives, such as those described in the Seventh Environment Action Programme (7th EAP) for living well within the ecological limits of the planet, the report *Transforming our world: the United Nations 2030 Agenda for Sustainable Development*, and the Innovation Agenda of the European Union.

This report explores possible synergies, tensions, gaps and trade-offs between the bio- and circular economies' objectives and actions. The policy context in Europe is discussed in Chapter 1, and the evolving bioeconomy in Europe is described in Chapter 2. Chapter 3 summarises the sustainability challenges related to a bioeconomy and makes the case for further integrating bio- and circular economy initiatives. Chapter 4 presents some concrete examples of how that could be done. Chapter 5 then takes a broader view to highlight the importance of tackling challenges at the systems level and concludes by presenting a set of system design principles for a circular bioeconomy.

This report by no means strives to be fully comprehensive, given the extensive literature that exists on major cross-cutting aspects, including the food system, renewable energy, waste treatment, chemicals and bioplastics. Rather than providing in-depth information, it attempts to illustrate the bigger picture, identifying the most pertinent issues and opportunities from a systemic perspective.

Key findings

The EU's 2015 Circular Economy Action Plan and its 2012 Bioeconomy Strategy both have food waste, biomass and bio-based products as areas of intervention. They also have concepts in common, such as the chain approach, sustainability, biorefining and the cascading use of biomass. Both of these policy agendas converge with respect to economic and environmental concerns, research and innovation, and societal transition towards sustainability.

The Bioeconomy Strategy, however, pays little attention to ecodesign and waste collection, sorting and suitability for high-grade recycling treatment. The link between chemicals legislation and non-toxic materials could also be more explicit. Furthermore, innovative business models and the role of small and medium-sized enterprises (SMEs) for closing local biomaterial loops would merit more attention. The Circular Economy Action Plan focuses mainly on the use of finite, abiotic resources. Biomass and bio-based products are a priority, but an encompassing approach to their application and wider sustainability aspects, including biodiversity impacts and nutrient cycles, is lacking.

The bioeconomy is substantial and resource intensive. In 2014, it accounted for 9 % of the total economy in terms of employment and revenues in 2014 (Ronzon et al., 2017), while biomass accounted for

([1]) For this and other definitions please refer to the glossary on p. 9.

more than 25 % of total material flows. Agriculture constitutes about 63 % of the total biomass supply in the EU, forestry 36 % and fisheries less than 1 % (Gurria et al., 2017). Wood-based materials, polymers, textiles and fibres/polymers in composite materials are the four main types of biomaterial used in the EU. Between 118 and 138 million tonnes of biowaste are generated annually (EC, 2010a), with a high share of food waste (100 million tonnes produced in 2012) (FUSIONS, 2015). About 25 % of this biowaste is collected and recycled.

The bioeconomy is rapidly evolving, especially in the areas of bioplastics and biocomposites. Some bioplastics are biodegradable, but many are not. Bioplastics production as a proportion of total plastics production is still low, currently below 1 %. In 2019, less than 20 % of bioplastics are expected to be biodegradable, with improper collection and sorting of plastics hampering recycling. Biocomposites (wood-plastic composites and natural fibre composites) account for 15 % of the total European composite market (Carus et al., 2015). The use of biocomposites is expected to increase further, e.g. in the automotive industry, but their recycling is also problematic.

Agriculture, forestry and fisheries already have substantial impacts on soil, water and air quality, biodiversity and landscape amenity value. Further expanding the bioeconomy in response to the increasing global demand for food, feed, biomaterials and bioenergy could lead to demand/supply conflicts and shifts in the land availability for food, biomaterial or bioenergy production. A sustainable and circular bioeconomy would keep resources at their highest value for as long as possible through cascading biomass use and recycling, while ensuring that natural capital is preserved. This requires coordinated action and careful consideration of possible trade-offs.

Approximately 72 % of the net annual increment of forests is currently harvested, pointing at a limited potential for the increased sourcing of wood biomass. As for agriculture, a shift to farming practices that either do not, or to a limited extent, rely on chemical inputs could contribute to nutrient circularity, although this may limit productivity. By shifting to alternative (aquatic) sources of biomass and more effectively using biowaste and residues, the resource base could be extended without the need for additional land for biomass production. Consumers can also play a role in creating a more sustainable bioeconomy, for instance by changing consumption patterns (e.g. reducing meat consumption), preventing food waste and separating biowaste from other waste streams so that it can be (partly) converted to fertiliser by composting or digestion.

Promising innovations and strategies for circular biomass use include biorefinery, three-dimensional (3D) printing with bioplastics, multipurpose crops, valorising residues and food waste, and biowaste treatment. The supporting policies are still loosely connected, and more synergy could be created. Aspects that appear to be underrepresented are product and infrastructure design, and collaboration among the actors throughout the value chain. Policy interventions should aim to reduce environmental pressures along the entire product life cycle. Second, bio-based approaches should be tailored to the specific use context in order to maximise the benefits of bio-based and biodegradable products. Finally, technological innovation should be embedded in wider system innovation that also tackles consumer behaviour, product use and waste management.

Abbreviations

3D	Three-dimensional
7th EAP	Seventh Environment Action Programme
ABS	Acrylonitrile butadiene styrene
CA	Cellulose acetate
CO_2	Carbon dioxide
CSCT	Centre for Sustainable Chemical Technologies
EC	European Commission
ECN	European Compost Network
EEA	European Environment Agency
EU	European Union
EU-28	The 28 Member States of the EU as of 1 July 2013
FAO	Food and Agriculture Organization of the United Nations
FEBA	Fédération Européenne des Banques Alimentaires/European Association of Food Banks
FP7	Seventh Framework Programme for Research and Technological Development
GDP	Gross domestic product
HDPE	High-density polyethylene
ICT	Information and communication technologies
INPAT	Impact noise insulating panel from textile industry waste
LDPE	Low-density polyethylene
NFC	Natural fibre composites
PA	Polyamide
PBAT	Poly (-butylene adipate-co-terephthalate)
PBS	Polybutylene succinate
PC	Polycarbonate

PCL	Polycaprolactone
PE	Polyethylene
PEF	Polyethylene furanoate
PET	Polyethylene terephthalate
PHA	Polyhydroxyalkanoate
PHB	Polyhydroxybutyrate
PLA	Polylactic acid or polylactide
PP	Polypropylene
PTT	Polytrimethylene terephthalate
PS	Polystyrene
PUR	Polyurethane
R&D	Research and development
SME	Small and medium-sized enterprise
UN	United Nations
WPC	Wood-plastic composite
WRAP	Waste and Resources Action Programme

Glossary

Abiotic	Physical rather than biological; not derived from living organisms.
Bio-based	A material or product that is (partly) derived from biomaterials.
Biocomposites	Composites made of a mixture of plastic polymers and natural fibres derived from wood (wood-plastic composites (WPCs)) or agricultural crops (natural fibre composites (NFCs)) (Carus et al., 2015).
Biodegradable	A material that can be degraded by microorganisms. This concept is not technically defined, in contrast with the term **compostable**.
Bioeconomy	The bioeconomy encompasses the production of renewable biological resources and their conversion into food, feed, bio-based products and bioenergy. It includes agriculture, forestry, fisheries, food, and pulp and paper production, as well as parts of the chemical, biotechnological and energy industries. Its sectors have a strong innovation potential because of their use of a wide range of sciences (life sciences, agronomy, ecology, food science and social sciences), enabling industrial technologies (biotechnology, nanotechnology, information and communication technologies (ICT), and engineering), and local and tacit knowledge (EC, 2012).
Biomass	Organic, non-fossil material of biological origin that can be used as biogenic feedstock in food supply, other products and for generating energy in the form of heat or electricity (Eurostat, 2018a).
Biomaterials	Materials made of biological resources.
Bioplastics	Bioplastics comprise both **biodegradable** and **bio-based** plastics.
Biopolymers	Polymers produced from living organisms that are biodegradable.
Biorefinery	IEA Bioenergy Task 42 definition: biorefining is the sustainable processing of biomass into a spectrum of marketable food and feed ingredients, bio-based products (chemicals, materials) and bioenergy (biofuels, power and/or heat) (IEA Bioenergy, 2014b).
Biowaste	Biodegradable garden and park waste, food and kitchen waste from households, offices, restaurants, wholesale, canteens, caterers and retail premises and comparable waste from food processing plants (EC, 2018b).

Cascading	Cascading is a strategy for using wood and other biomass in a more efficient way by reusing residues and recycled materials in sequential steps for as long as possible, before turning them into energy. Cascading extends the total biomass resource base within a given system (Vis et al., 2016). Different definitions of cascading exist in the literature. The concept was introduced in the 1990 (Sirkin and ten Houten, 1994) and further elaborated on by different authors. Often, a differentiation is made between cascading-in-time, -in-value or -in-function (Odegard et al., 2012; Keegan et al., 2013). Furthermore, a differentiation can be made between single-stage and multistage cascades, depending on the number of material applications before a biomass resource is turned into energy (Essel et al., 2014). Cascading-in-time is the most commonly used concept and is used in this report when mentioning 'cascading'.
Chitin	A fibrous substance consisting of polysaccharides; it is the major constituent of the exoskeleton of arthropods and the cell walls of fungi.
Circular economy	An economy that is restorative and regenerative by design. It aims to maintain the utility of products, components and materials, and retain their value (Ellen MacArthur Foundation, 2013).
Compostable	Materials that can be degraded by microorganisms under specific conditions into carbon dioxide (CO_2), water and other basic elements, as defined in technical standards, such as EN13432 for Europe.
End-of-waste	When certain waste ceases to be waste and obtains the status of a product.
Eutrophication	Excessive richness of nutrients in water bodies, which induces growth of plants and algae and, because of the biomass load, may result in oxygen depletion of the water body.
Food waste	All food as defined in Article 2 of Regulation (EC) No 178/2002 of the European Parliament and of the Council that has become waste (EC, 2018b).
Food loss	A decrease in the mass or nutritional value (quality) of food that was originally intended for human consumption. These losses are mainly caused by inefficiencies in food supply chains, such as poor infrastructure and logistics, lack of technology, insufficient skill, knowledge or management capacity of supply chain actors, and a lack of access to markets. In addition, natural disasters can contribute to food losses (FAO, 2013).
Food wastage	Any food lost by deterioration or waste. Thus, the term **wastage** encompasses both food loss and food waste (FAO, 2013).
Leachate	A **leachate** is the solution resulting from leaching by percolating ground water. It contains soluble components from soil, landfill etc.
Platform chemical	Chemical building blocks that can be converted into a wide range of chemicals or materials.
Polymer	A polymer is a large molecule, or macromolecule, composed of many repeated subunits. Because of their broad range of properties, both synthetic and natural polymers play essential and ubiquitous roles in everyday life.
Side stream	A stream that is the result of an intermediate step of the production process.
Valorise	Enhance or try to enhance the price, value or status of a material or product.

1 The bio- and circular economies: two complementary policy strategies

The bioeconomy comprises any value chain that uses biomaterial and products from agricultural, aquatic or forestry sources as a starting point. Shifting from non-renewable resources to biomaterial is an important innovation aspect of the circular economy agenda. The bioeconomy and the circular economy are thus conceptually linked. This chapter introduces the policy concepts and explores synergies and tensions.

Key points ([2]):

- Circular and bioeconomy policies have strong thematic links, both having, for example, food waste, biomass and bio-based products as areas of intervention.
- The Circular Economy Policy Package aims to close material loops through the recycling and reuse of products, effectively reducing virgin raw material use and associated environmental pressures.
- The Bioeconomy Strategy is a research and innovation agenda aimed at enhancing the exploitation of biomaterials in a sustainable way.
- Both policy agendas converge with respect to economic and environmental concerns, research and innovation, and societal transition towards sustainability, but synergies could improve.
- The Bioeconomy Strategy pays little attention to ecodesign, waste management and recycling aspects and the role of innovative business models in these respects. The link with chemicals legislation and non-toxic materials could also be more explicit.
- The Circular Economy Action Plan mentions biomass and biomaterials as a priority, but an encompassing approach to their sustainable application, including biodiversity aspects and nutrient cycles, is lacking.
- Exploiting biomass is not necessarily circular and sustainable. Processed biomaterials are not always biodegradable, and mixing them with technical materials can hamper recycling. In addition, exploitation of biomaterials may increase pressure on natural resources and dependence on use of non-biological materials with considerable environmental impact, such as agrichemicals.

1.1 The European Union's Bioeconomy Strategy

On 13 February 2012, the European Commission (EC) launched a communication entitled *Innovating for sustainable growth: a bioeconomy for Europe*. This bioeconomy strategy document provided a framework to stimulate knowledge development, research and innovation on the conversion of renewable biological resources into products and energy (EC, 2012).

The communication defines the bioeconomy as the production of renewable biological resources and their conversion into food, feed, bio-based products and bioenergy. It includes agriculture, forestry, fisheries, food, and pulp and paper production, as well as parts of [the] chemical, biotechnological and energy industries. Its sectors have a strong innovation potential due to their use of a wide range of sciences (life sciences, agronomy, ecology, food science and social sciences), enabling industrial technologies

([2]) See body text for references.

(biotechnology, nanotechnology, information and communication technologies (ICT), and engineering), and local and tacit knowledge (EC, 2012).

The Bioeconomy Strategy aims to contribute to solving several societal challenges: ensuring food security, managing natural resources sustainably, reducing dependence on non-renewable resources, mitigating and adapting to climate change, creating jobs and maintaining European competitiveness. This would require a coherent European Union (EU) bioeconomy policy framework, however the strategy itself does not necessarily provide one. Instead, the focus is on improving the knowledge base by investing in research, innovation and skills for new technologies and processes; bringing together stakeholders in, for example, the EU's Bioeconomy Panel and Bioeconomy Observatory in order to create more coherence; and creating markets and competitiveness. The revision of the Bioeconomy Strategy in 2018 provides an opportunity to create a more coherent policy framework.

As is shown in Table 1.1, the EU's Bioeconomy Strategy, Innovating for sustainable growth: a bioeconomy for Europe, is complemented by several other EU policy initiatives relevant to the bioeconomy. These policy strategies focus on different aspects of the bioeconomy, including the agricultural, forestry, energy, food and bio-based industries.

Policies related to bioeconomy cover a variety of focal areas (Priefer et al., 2017). Some bioeconomy initiatives, such as the Bioeconomy Strategy, deal with all uses (food, feed, materials and energy), while others, such as the Energy Roadmap, deal with only one or two uses. Other contrasts exist regarding the emphasis given to specific economic sectors. One approach is to focus on one sector, such as chemicals, and look at the bioeconomy as a catalyst for innovation and economic growth by making 'better' (economic) use of biomaterials. Another approach looks at the bioeconomy as an engine of rural development, focusing on agriculture, fisheries, forestry and aquaculture.

As pressures on ecosystems and biodiversity increase in the EU, it is essential to find a balance between different uses of biomass, as well as between its economic valorisation and preserving and enhancing ecosystem services, including soil quality, biodiversity, water quality and availability. There is a risk that sectoral approaches are incoherent and miss out on opportunities and synergies. Combined, such narrow approaches can also contribute to overexploitation of biomass and further ecosystem degradation across the EU. This is increasingly recognised, for example in the debates on bioenergy (HLPE, 2013) and the reform of the common agricultural policy (EC, 2017b).

1.2 The EU Circular Economy Action Plan

A circular economy seeks to increase the proportion of renewable or recyclable resources and reduce the consumption of raw materials and energy in the economy, while, at the same time, protecting the environment through cutting emissions and minimising material losses. Systemic approaches, including the ecodesign, sharing, reusing, repairing, refurbishing and recycling of existing products and materials, can play a significant role in maintaining the utility of products, components and materials, and retaining their value (EEA, 2016).

The EC launched the Circular Economy Package in 2015 (EC, 2015a), defining the circular economy as an economy where the value of products, materials and resources is maintained for as long as possible and where the generation of waste is minimised. The policy package aims to close material loops through the recycling and reuse of products. This will reduce the dependency on virgin raw materials as well as the environmental pressures associated with material use, thus resulting in economic and environmental co-benefits.

Within this package, the Commission communication 'Closing the loop — An EU action plan for the circular economy' (EC, 2015a) focuses on actions related to production, consumption, waste management, stimulating markets for secondary raw materials and water reuse. This provides incentives for circular product design and production, and for stimulating consumption of products with lower environmental impacts. The action plan's five priority areas are (1) plastics, (2) food waste, (3) critical raw materials, (4) construction and demolition waste, and (5) biomass and bio-based products. There is also a focus on innovation, investment, and horizontal measures and monitoring.

This 2015 communication clearly relates to the 2011 Roadmap to a Resource Efficient Europe (EC, 2011). Both the 2015 communication and this roadmap form part of a history of European policy strategies that focus on better waste and resource management, such as the thematic strategies on waste prevention and recycling, and on the sustainable management of natural resources.

In support to the implementation of the 2015 Communication 'Closing the loop — An EU action plan for the Circular Economy', and as part of its

Table 1.1 EU policy strategies relevant to the bioeconomy

Strategies relevant to the bioeconomy	
Bioeconomy (horizontal)	Commission communication *Innovating for sustainable growth: a bioeconomy for Europe* (2012)
Sustainability	Seventh Environmental Action Programme (2014)
Sectors supplying biomass	
Agriculture	Commission communication *The CAP towards 2020: meeting the food, natural resources and territorial challenges of the future* (2010)
Forestry	Commission communication *A new EU forest strategy: for forests and the forest-based sector* (2013) Commission staff working document *Multiannual implementation plan of the new EU forest strategy* (2015)
Fisheries, aquaculture and algae	Commission communication *Reform of the common fisheries policy* (2011) Commission communication *Blue growth: opportunities for marine and maritime growth* (2012) Commission communication *Strategic guidelines for the sustainable development of EU aquaculture* (2013)
Waste	See cross-cutting policies (below)
Sectors using biomass	
Food security	Commission communication *An EU policy framework to assist developing countries in addressing food security challenges* (2010) Commission communication *Increasing the impact of EU development policy: an agenda for change* (2011) Commission communication *Enhancing maternal and child nutrition in external assistance: an EU policy framework* (2013) Commission communication *The EU approach to resilience: learning from food security crises* (2012)
Bioenergy	Commission communication *An energy policy for Europe* (2007) Commission communication *A European strategic energy technology plan (SET-plan) — Towards a low-carbon future* (2007) Commission communication *Limiting global climate change to 2 degrees Celsius — The way ahead for 2020 and beyond* (2007) Commission communication *Energy 2020 — A strategy for competitive, sustainable and secure energy* (2010) Commission communication *Energy roadmap 2020* (2011) Commission communication *A policy framework for climate and energy in the period from 2020 to 2030* (2014) Commission communication *Accelerating Europe's transition to a low-carbon economy* (2016) Commission communication *The role of waste-to-energy in the circular economy* (2017)
Bio-based industries	Commission communication *A lead market initiative for Europe* (2007) Commission communication *Preparing for our future: developing a common strategy for key enabling technologies in the EU* (2009) Commission communication *A stronger European industry for growth and economic recovery* (2012) Commission communication *For a European industrial renaissance* (2014)
Cross-cutting policies relevant to the bioeconomy	
Climate change and energy	See bioenergy (above)
Circular economy — waste	Commission communication *Towards a circular economy: a zero waste programme for Europe* (2014) Commission communication *Closing the loop — An EU action plan for the circular economy* (2015) Commission communication *The role of waste-to-energy in the circular economy* (2017) Commission communication *Future strategy on plastics use, reuse and recycling* (2016) Directive (EU) 2015/720 of the European Parliament and of the Council of 29 April 2015 amending Directive 94/62/EC as regards reducing the consumption of lightweight plastic carrier bags
Biodiversity	Commission Communication *Our life insurance, our natural capital: an EU biodiversity strategy to 2020* (2011)
Regional policies — smart specialisation	Commission communication *Regional policy contributing to smart growth in Europe 2020* (2010)
Research and innovation	Commission communication *Europe 2020 flagship initiative — Innovation union* (2010)
Biodiversity	EU Biodiversity Strategy to 2020 (2011)
Resource efficiency	EU Roadmap to a Resource Efficient Europe (2011)

Source: Ronzon et al. (2017) with additional references.

continuous effort to transform Europe's economy into a more sustainable one, in January 2018 the European Commission adopted the so-called 2018 Circular Economy Package. This includes, among others, a Monitoring Framework on progress towards a circular economy at EU and national level (EC, 2018a). It is composed of a set of ten key indicators that cover aspects related to e.g. waste generation, food waste, recycling, trade, raw materials, investments and jobs.

1.3 Linkages

Reading across the key policy documents, important lessons can be drawn that shed some light on the potential for the bio- and circular economies to become partners in sustainability.

1.3.1 Shared concepts/synergies

There are clear links between the 2015 Circular economy Action Plan and the 2018 Circular Economy Policy Package and the 2012 Bioeconomy Strategy, which both have food waste, biomass and bio-based products as areas of intervention. They also have concepts in common, such as the chain approach, sustainability, biorefining, resource efficiency, the cascading use of biomass, tackling production and consumption, and considering the global dimension.

The 2015 Circular Economy Action Plan called for an analysis of the synergies, and for a corresponding update of the Bioeconomy Strategy. In turn, the concept of circularity was explicitly embraced by the European Bioeconomy Stakeholders in their 2017 manifesto:

> Bioeconomy and the circular economy need to go together to develop synergies between the two systems in order to ensure that resources are used more productively and efficiently in both economies. We want to cooperate to deliver the bioeconomy contribution to the goals, targets and ambitions formulated in the EU Circular Economy Package which offers great opportunities to make better and more efficient use of biomass resource and to reduce overall resource consumption. The Circular Economy Action Plan and its waste legislation should be fully implemented to minimise waste, to separately collect, reuse and transform bio-waste as well as by-products and residues into high-added-value compounds (European Bioeconomy Stakeholders Panel, 2017).

In addition to these recognised links, the Bioeconomy Strategy and the Circular Economy Action Plan deal with many converging issues, which can be grouped under different agendas:

- an economic agenda aimed at growth and job creation, stimulating investment, creating markets and a level playing field, and removing administrative burdens and legislative obstacles;
- a resource agenda that aims to find solutions for resource scarcity and security by stimulating sustainable production and consumption and the use of waste/residues/end-of-waste/secondary raw materials as inputs for a variety of applications and purposes;
- a research and innovation agenda focused on new knowledge, technologies and skills serving the economic and resource agendas;
- an environmental policy agenda that strives for more coherence by making links between different policy areas and issues (climate, ecosystems, biodiversity, quality of soils, etc.) and for a more systemic approach;
- an agenda that enables a societal transition; a full chain approach, stakeholder involvement, awareness raising at consumer level and support for public-private partnerships should ensure an uptake of the transition throughout society.

1.3.2 Deviating concepts/possible tensions

Some key issues appear to be underexplored in both the Bioeconomy Strategy and the Circular Economy Package.

The Bioeconomy Strategy pays little attention to product design for repair, reuse, recycling, durability and preventing wastage. In addition, innovative forms of consumption (collaborative economy, product service combinations) receive little consideration even though examples from the bio-based industry could inspire others. Furthermore, waste management is addressed by implicit reference to the so-called 'waste hierarchy' (EU, 2008) but not in terms of implications for collection, sorting and suitability for high-grade recycling treatment. Paying more attention to this innovation aspect could lead to more use of biomass residues, cascading and circularity. The link between chemicals legislation and non-toxic materials is not made explicit either. Chemicals are used in bio-based products and hence their use could pose challenges to circularity objectives, for example by hampering the establishment of clean biomaterial cycles. On the other hand, the use of bio-based materials could also drive a general reduction of the use of hazardous substances. Finally, the role of SMEs in the bioeconomy is not widely discussed, even though they could play a particular role in terms of innovation and by being key actors in closing local biomaterial loops.

The 2015 Circular Economy Action Plan focuses mainly on the use of finite, abiotic resources and how they can be reused and recycled for as long as possible. Even though the plan identifies biomass and bio-based products as a priority, there is no encompassing approach towards a circular *bio*economy. The plan includes guidance on the cascading of wood, a target for recycling wood packaging, an obligation to collect biowaste separately and a reference to food waste reduction targets, but does not elaborate on wider sustainability aspects. As such, the potential contribution of the bioeconomy to the circular economy is not thoroughly explored. On the other hand, the value of biodegradable products is, almost by definition, harder to preserve than for non-biodegradable products, which limits the applicability of the core CE concept to bio-materials. In this respect, the time dimension of bio-material cycles, that is very different from technical materials, would also need to be taken into account more systematically when assessing the ecosystem impacts of different use models.

1.3.3 Popular notions

As the concepts of bio- and circular economy have gained traction, two popular views have emerged: (1) the bioeconomy is circular by its nature and (2) biological and technical materials should be kept in separate cycles. To what extent do these views hold?

The bioeconomy is circular by nature

Biological resources are embedded in the natural biological cycle, which is regenerative and without waste. Using biomaterials is therefore viewed as contributing to the circular economy in the context of innovation policy or the Circular Economy Action Plan (e.g. EBCD, 2017). However, this general notion does not account sufficiently for sustainability issues, as a shift to biomaterials may exacerbate the overexploitation of natural resources or the disturbance of nutrient cycling. Furthermore, processed biomaterials are not necessarily biodegradable, as is the case for some bioplastics. Where biomaterials and technical materials are mixed, recycling can be hampered (although this is not necessarily the case). Finally, the exploitation of biomass may in effect depend on the use of non-biological materials with considerable environmental impact, such as agrichemicals.

The two-cycle principle

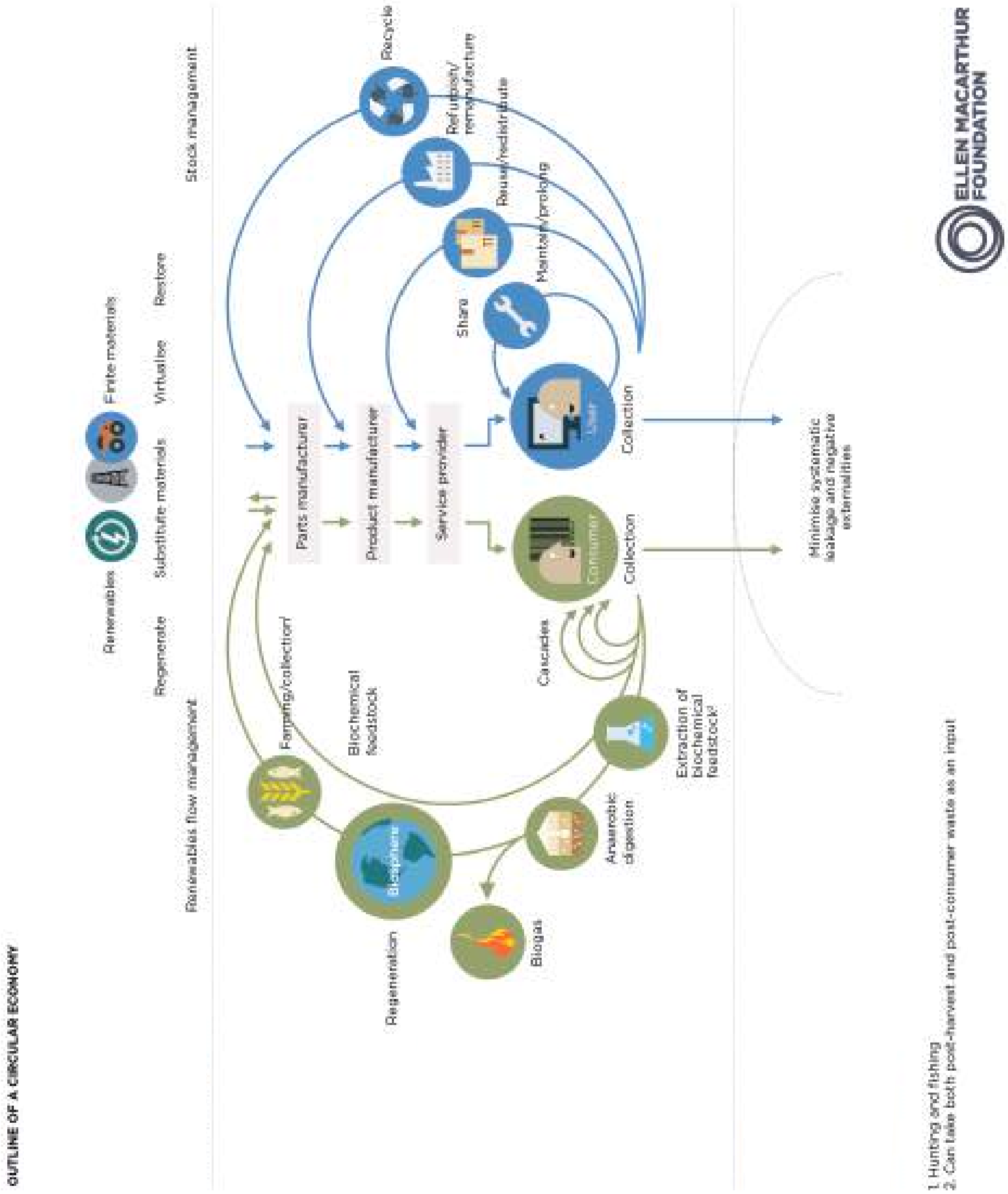
The notion that biological resources, because of their regenerative nature, should cycle separately from abiotic or technical materials was put forward by Michael Braungart and William McDonough in their Cradle2Cradle philosophy (Braungart and McDonough, 2002). Later, the Ellen MacArthur Foundation incorporated this concept in its graphic presentation of the circular economy that distinguishes between biological resources, which can be recycled through the biosphere, and technical resources, which can be recycled through closed loops (Ellen MacArthur Foundation and McKinsey Center for Business and Environment, 2015) (Figure 1.1).

In the technical cycle, abiotic materials — once mined — need to remain in the cycle for as long as possible, not only by recycling, but also by using the inner circles (maintenance, reuse, remanufacturing, refurbishment), keeping the value of materials as high as possible throughout their life cycle. The biological cycle focuses on optimising their use by cascading and the extraction of biochemicals, while returning their nutrients to the biosphere through composting or anaerobic digestion, recovering biogas where possible. In this context it should be noted that the international trade of biomaterials leads to a reallocation of nutrients, which can create unwanted impacts on local ecosystems.

In practice, the distinction between the technical and biological cycle is not always that clear. For instance, many products are composed of biomaterials, such as wood, and abiotic materials, such as metals. Furthermore, biomaterials can be turned into polymers that are not biodegradable, making them more characteristic of the technical cycle. Separating biological from technical materials would in principle make it possible to harness the full circular potential of biological resources. A strict separation is not necessary, however, where bio-based but non-biodegradable materials have similar material (and chemical) properties as their non-bio-based alternatives. In that case, they can be collected and treated in the same way.

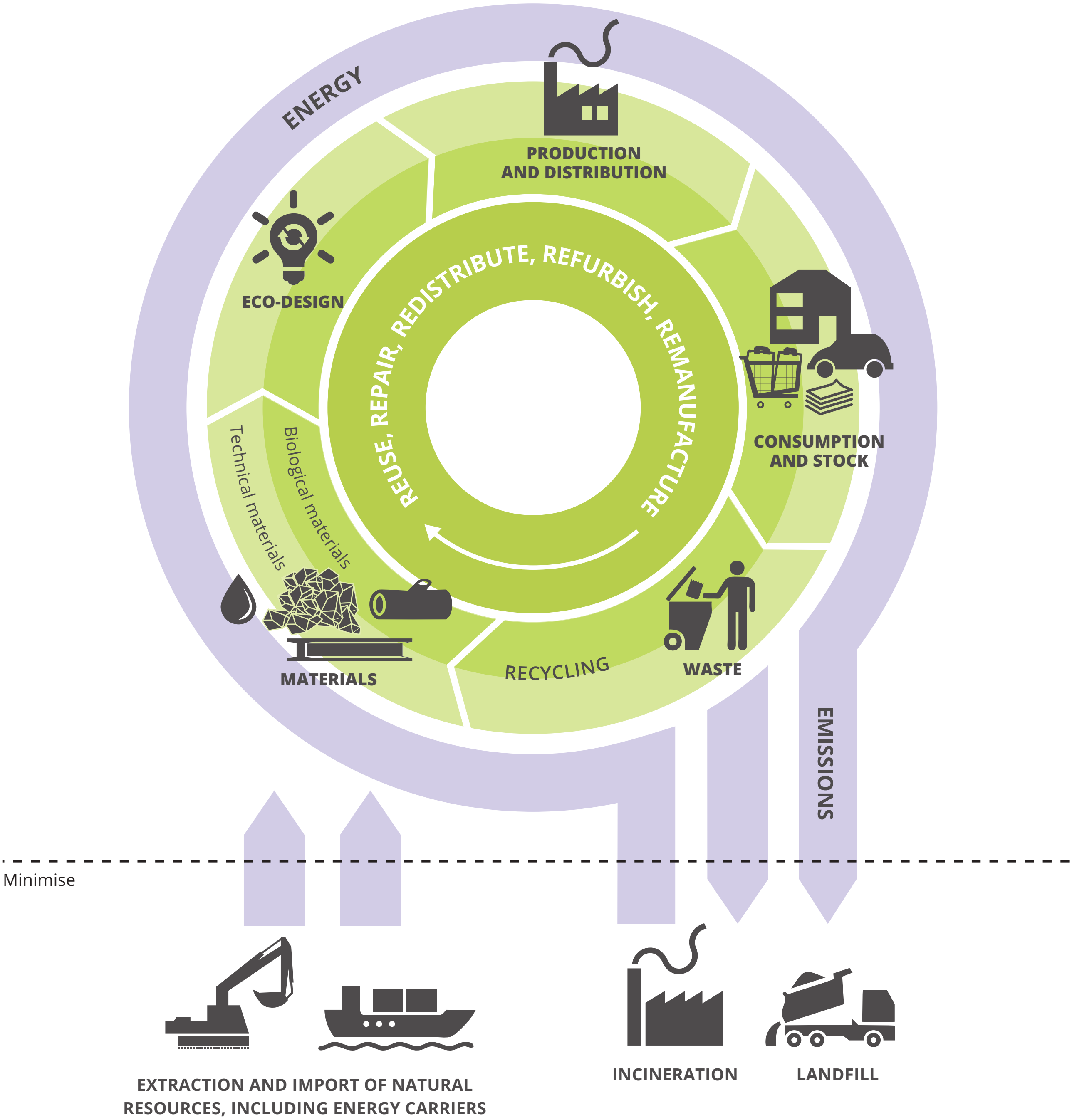
Finally, it should be noted that managing materials and products in a circular economy also requires energy, e.g. for the transportation and processing of products across two use cycles. To achieve a sustainable circular economy, the energy used should be renewable. This is a challenge that requires alignment between the circular economy and energy transitions. In the European Environment Agency's (EEA's) circular economy system diagram (Figure 1.2), energy flows are represented as the outermost circle, inside which materials (both bio- and technical materials — middle circles) and products (inner circle) circulate. Where biomass is used as a renewable energy source, the connection between the circular economy and energy transitions becomes very tangible, as the biomass allocated for renewable energy generated cannot be reused or recycled as material any longer.

Figure 1.1 The two-cycle view of the circular economy



Source: Ellen MacArthur Foundation and McKinsey Center for Business and Environment, 2015.

Figure 1.2 **Circular economy system diagram**



11.5 tonnes of materials per person were extracted in the EU in 2014 (direct material consumption).

3.0 tonnes of materials per person were imported to the EU in 2014 (direct flows).

0.3 tonnes of waste per person were incinerated in the EU in 2012.

2.2 tonnes of waste per person were sent to landfill in the EU in 2012.

Source: EEA, 2016.

2 Material use in the bioeconomy

The sectors exploiting biomass make up a substantial part of the economy. This chapter provides a brief overview of the current state of the bioeconomy in Europe, as well as its expected evolution in the short term. Extensive coverage of the characteristics and dynamics of the food system goes beyond the scope of this report. The focus here is primarily on biomaterials.

Key points ([3]):

- The bioeconomy is of a significant size and is resource intensive, in 2014 accounting for 9 % of employment and more than 25 % of total material flows.
- Agriculture constitutes about 63 % of the total biomass supply in the EU, forestry 36 % and fisheries less than 1 %. Food and feed account for 62 % of the EU's biomass use, with materials and energy each representing around 19 %.
- More than one third of primary biomass sourced from forests is directly used to produce energy. In total, 47 % of the EU's need for wood products and pulp and paper are met by secondary resources from recycling.
- The global production of plastics is estimated to account for about 7 % of the world's fossil fuel consumption. The proportion of bioplastics is still low, currently below 1 %. However, the worldwide biopolymer production capacity is forecast to increase from 6.6 million tonnes in 2016 to 8.5 million tonnes in 2021.
- Some bioplastics are biodegradable, but many are not. In 2019, less than 20 % of bioplastics are expected to be biodegradable. The proper collection and sorting of bioplastics poses problems in closing material loops.
- In 2012 biocomposites (wood-plastic composites (WPCs) and natural fibre composites (NFCs)) accounted for 15 % of the total European composite market. The use of biocomposites is expected to increase further, e.g. in the automotive industry, but their recycling is difficult.
- Between 118 and 138 million tonnes of biowaste are generated annually, of which 100 million tonnes is food waste. About 25 % is collected and recycled.

2.1 The bioeconomy today

The EU bioeconomy represented around 9 % of the total economy in terms of employment and revenues in 2014 (Ronzon et al., 2017), while biomass accounted for more than 25 % of total material flows (EU extraction and imports taken together). Thus, the physical basis of today's bioeconomy is relatively large compared with its economic output ([4]).

Figure 2.1 provides a closer look at the economic and physical dimensions of Europe's current bioeconomy. In economic terms, the production of food is the largest contributor, followed by the production of

([3]) See body text for references.
([4]) For an in-depth characterisation and analysis of the bioeconomy sectors and biomass flows, see Ronzon et al., 2017.

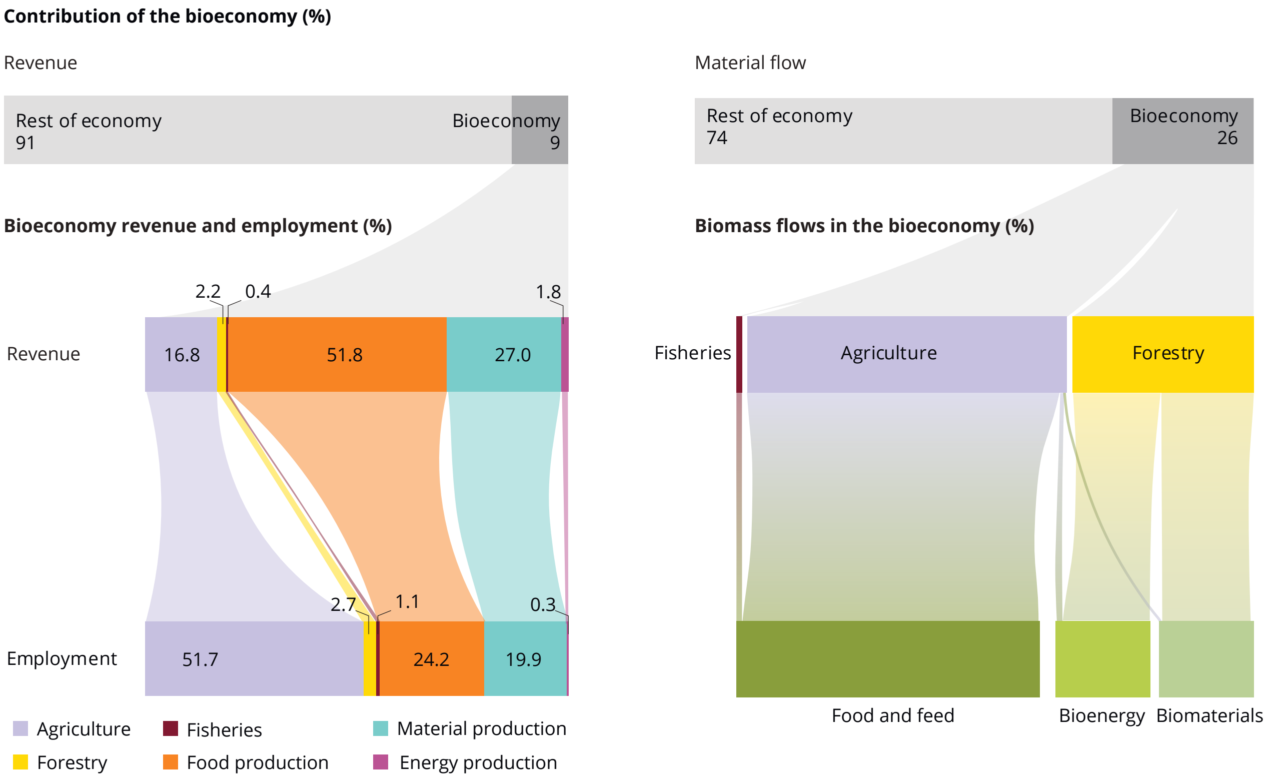
biomaterials, namely textiles, wooden products, paper and cardboard, plastics and chemicals. Of those employed in the bioeconomy, just over half work in agriculture, another 24 % in food production, and 20 % in the production of biomaterials. Bioenergy only plays a minor role, both in terms of revenues and in terms of employment.

In physical terms, agriculture constitutes about 63 % of the total biomass supply in the EU, forestry 36 % and fisheries less than 1 % (Gurria et al., 2017). Food and feed account for 62 % of the EU's biomass use, with materials and energy each representing around 19 %. Biomass for materials is almost entirely sourced from forests, with less than 0.1 % of agricultural biomass used for biomaterial production. Biofuel production uses about 2 % of agricultural biomass, or 18 times more than the amount used in biomaterial production (Gurria et al., 2017).

As for food, the EU is a major producer and net exporter of wine, olive oil, tomatoes, cereals, dairy products and meat. As for livestock production, poultry, veal and pig production are increasing, as opposed to beef, sheep and goat production. Major imports are tropical fruits, coffee, tea, cocoa, soy products and palm oil, as well as seafood and fish products. Apart from the impact on global fish stocks, European consumption has a global effect through the dependency on feed imports for its intensive livestock and aquaculture production. Approximately 11 million hectares (mainly in South America) were needed in 2011 for the production of imported soybeans (EEA, 2017b).

As for biomaterials, wood-based materials, polymers, textiles, and natural fibres or wood fibres mixed with polymers in composite materials are the four main biomaterials used in the EU.

Figure 2.1 Economic and physical dimensions of the current bioeconomy (2014) in the EU



Sources: JRC Biomass project; 2016 Bioeconomy report (Ronzon, et al., 2017); Eurostat MFA.

2.1.1 *Wood-based materials*

The wood-based sector produces materials for a variety of applications including construction materials, furniture, paper and cardboard and, in southern Europe, cork. It is the oldest and most developed of the biomaterial sectors in the EU. The sector has also developed a number of ways to recirculate waste flows (Mantau, 2012). The recycling of wood fibres has evolved into a cascading industrial system, in which fibres are downcycled from high- to lower-grade applications with energy recovery as the ultimate step. One example is the recovery of saw mill residues for use in particle boards. Another prominent example is the recycling of recovered paper (Figure 2.2).

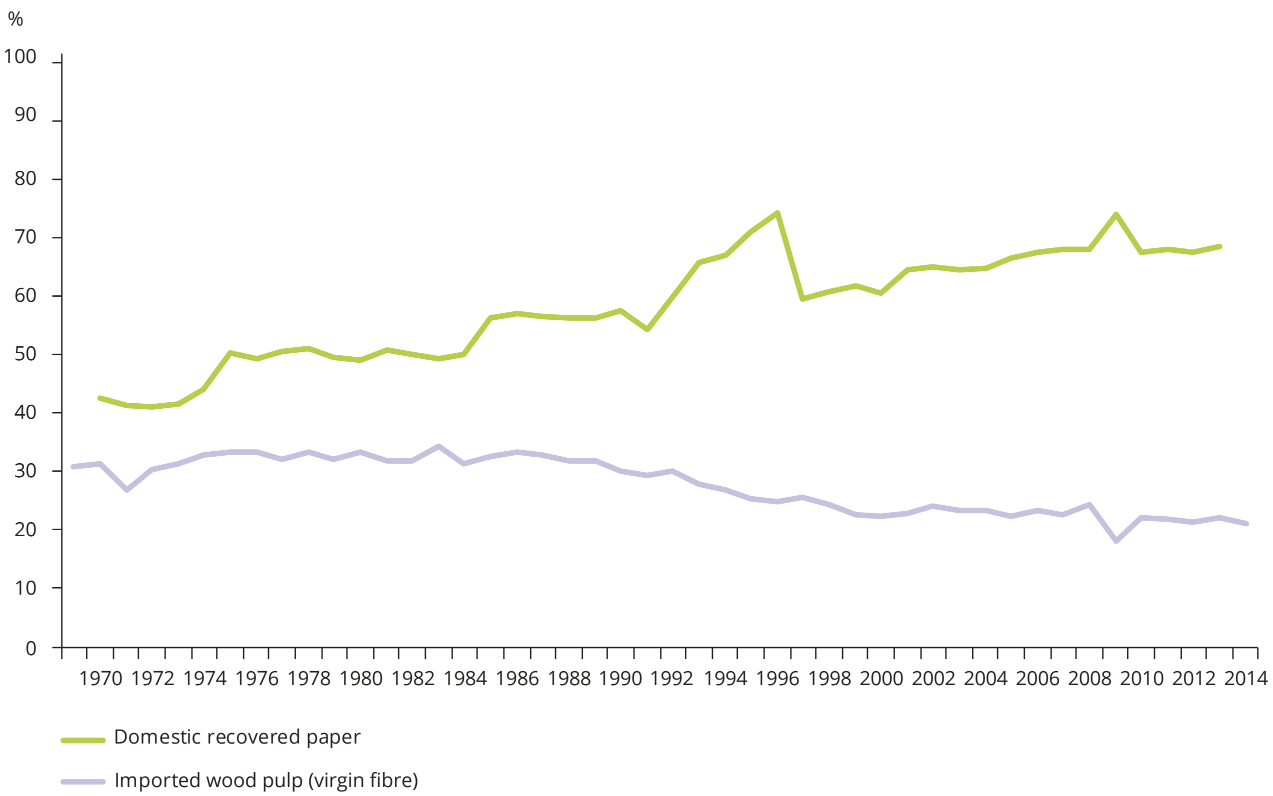
Figure 2.3 provides a simplified overview of biomass resource flows in EU wood-based value chains, based on Mantau (2012). A little over one third of primary biomass sourced from forests is directly used to produce energy. On the other hand, 47 % of the EU's need for wood products and pulp and paper are met by secondary resources from industrial (pre-consumer) and post-consumer recycling — 26 % and 21 %, respectively.

Paper production is already highly circular, but Figure 2.3 shows that the recycling rate of wood products is relatively low. This can be partly explained by, for example, the long life of furniture or construction wood, effectively sequestering carbon by taking resources out of economic flows. Another important factor is the lack of collection systems. In any case, a greater proportion of such products is used for energy recovery than for recycling.

2.1.2 *Polymers*

The production and use of bio-based polymers in the EU is relatively new, except for a number of traditional natural polymers, such as starch and natural rubber. A main technological innovation within the chemical industry is the refining of biomass into feedstock chemicals in search of renewable alternatives to fossil-based materials and energy. In that context, bio-based polymers have probably been the most relevant drivers for the development of the EU research and policy agenda related to bioeconomy.

Figure 2.2 Recovered paper and imported wood pulp as a proportion of total paper production in Germany



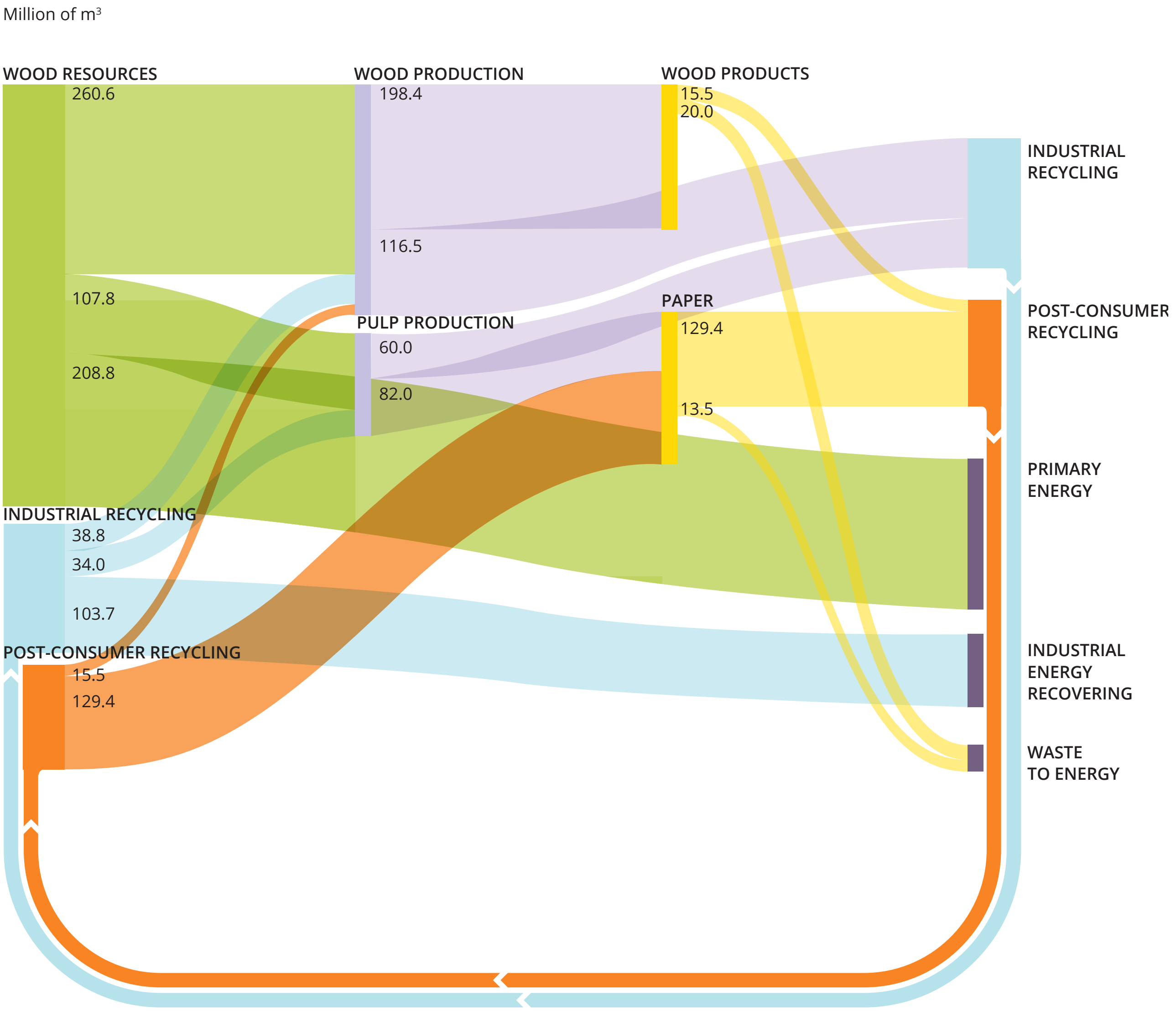
Source: Own calculations based on FAOSTAT (the database of the Food and Agriculture Organization of the United Nations) data.

Current production and consumption levels of bio-based polymers are low compared with other bioeconomy sectors and the fossil fuel sector. In 2016, 13 % of the world's fossil fuel consumption (coal, natural gas and oil) was used for non-energy purposes (IEA, 2016), mainly as a feedstock for the chemical industry. The global production of plastics is estimated to account for about 7 % of the world's fossil fuel consumption (van den Oever et al., 2017), while the production capacity for bio-based and biodegradable plastics, of which Europe currently holds 27 %, accounts for nearly 1 % (about 4.2 million tonnes) of global plastics production (European Bioplastics, 2017; van den Oever et al., 2017).

Bioplastics are currently mainly sourced from agricultural biomass, primarily maize, sugar cane and wheat (WEF et al., 2016). A shift is, however, occurring towards biomass from plants that are not suitable for food or animal feed production, for instance crop residues such as maize stalks, leaves and cobs, waste vegetable oils, biowaste, pulp and cellulose. In addition, biomass derived from algae is being investigated, as it does not rely on agricultural land and has a higher growth yield than land-based feedstock.

The term bioplastics comprises both biodegradable and bio-based plastics (Figure 2.4). According to the Organisation for Economic Co-operation and

Figure 2.3 Overview of wood-based resource flows in the EU



Source: Based on data from Mantau (2012).

Development (OECD) definition, biodegradable plastics are materials that can be biotransformed and decomposed by microorganisms into water, naturally occurring gases, such as carbon dioxide (CO_2) and methane (CH_4), and biomass (e.g. new microbial cellular constituents). This process depends on the surrounding environmental conditions (the environmental medium and temperature). Bio-based plastics are fully or partly made from renewable resources such as starch, sugar and vegetable oils. Some bio-based polymers are biodegradable, for example polylactic acid (PLA), but many, such as biopolypropylene (PP), biopolyethylene (PE) and biopolyethylene terephthalate (PET), are not. The latter polymers are also called drop-in bio-based polymers, as they have exactly the same structure as their fossil counterparts and can thus be easily substituted and integrated into existing plastics production systems and applications. Fossil-based biodegradable polymers exist as well, for example polybutylene adipate-co-terephthalate (PBAT), which is used for food packaging, compostable plastic bags for gardening and agricultural use, and as a water-resistant coating for certain products, such as paper cups.

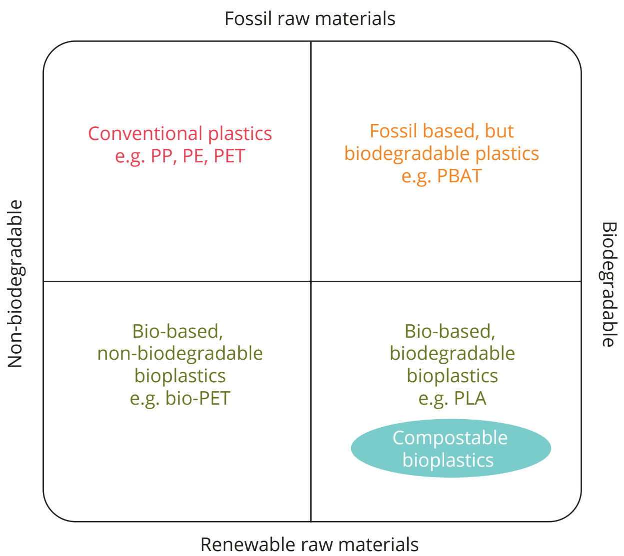
Within the broad term of biodegradability, industrially compostable materials are a category of biomaterials defined by different standards in different regions (EN13432 for Europe, ASTM D400 and D6868 for the United States). Such standards include criteria for whether or not a material is industrially compostable (WEF et al., 2016), that is, if it biodegrades by at least 90 % by weight within six months under controlled composting conditions, it fragments into pieces smaller than two mm diameter under controlled composting conditions within 12 weeks and the compost obtained at the end of the process has no negative effects on plant growth. In addition to industrially compostable materials, home compostable materials are defined as well. These are industrially compostable, but can be treated at ambient temperatures and the timeframes for biodegradation and disintegration can be longer. Moreover, parameters such as moisture content, aeration, acidity and the carbon-to-nitrogen ratio do not need to be controlled.

With 30% bio-based material, the most prominent bioplastic produced is bio-PET, used for bottles, followed by cellulose acetate (CA), used for cellophane film, and PBAT and PLA, used for various kinds of packaging (see Figure 2.6).

The main application of bioplastics is in packaging — 39 % or 1.6 million tonnes (Figure 2.5). Uptake within other sectors for, for example, consumer, automotive and construction products, is increasing (Nova Institut, 2014; European Bioplastics, 2017). In 2015, about 100 000 tonnes of biodegradable plastics, mainly starch based and PLA co-polymers, were produced, mainly for compostable shopping and waste collection bags (Kaeb et al., 2016).

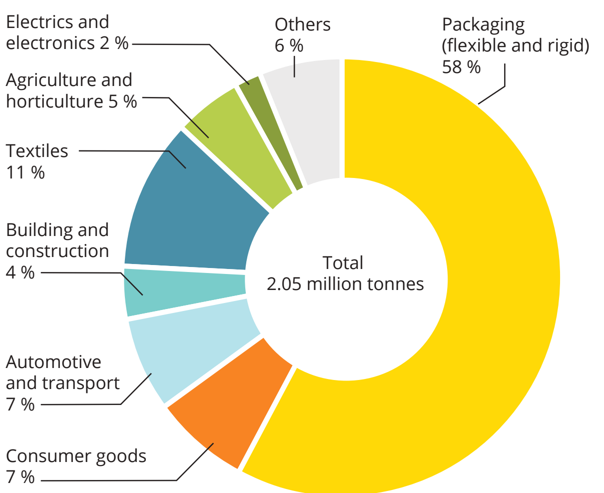
Issues with the proper collection and sorting of plastics poses problems for closing bioplastic material loops. Erroneous classification at the point of disposal, for example of PLA and PET9, can contaminate biowaste streams unintentionally.

Figure 2.4 Bio-based and biodegradable plastics: what is the difference?



Source: EEA, 2018.

Figure 2.5 Global production capacities of bioplastics, 2017, by market segment



Note: More information: www.bio-based.eu/markets and www.European-bioplastics.org/market.

Source: European Bioplastics, nova-Institute (2017).

2.1.3 Biocomposites

Composite materials are those made from two or more different materials with distinct properties, yielding materials with new combinations of properties. In the context of the bioeconomy, relevant biocomposites are WPCs and NFCs. In 2012, biocomposites accounted for 15 % of the total European composite market, with roughly two thirds being WPCs and one third being NFCs.

The main applications are in construction, for decking boards, panels and fences, furniture, and fixtures and fittings. Cotton, flax and hemp are among the main sources of natural fibres used in NFCs in the automotive industry (Carus et al., 2015). In general, biocomposites are very difficult to recycle because separating the fibres from the polymer material is virtually impossible without destroying the fibre structure and/or the polymer integrity.

2.1.4 Textiles

Fibres for textile use have traditionally been bio-based, sourced from crops such as cotton, hemp and jute; animals in the case of wool, silk and leather; or processed from natural polymers for the production of viscose and acetate. With the advent of the petrochemical industry, however, synthetic fibres such as polyester, nylon/polyamide, acrylic and polypropylene have become common materials in the production of clothing, floor coverings and home furnishings, as well as in industrial textiles.

Between 2012 and 2016, about 33 % of fibres used in the 28 Member States of the EU (EU-28) came from cotton and wool, 36 % from jute, flax and other bio-based fibres, and 31 % were synthetic or artificial fibres. Over the same period, 77 % of spun fibres came from cotton or wool, while 23 % were synthetic or artificial fibres (Eurostat, 2017). These data reflect only the use of fibres in European industry, rather than the final consumption of finished textiles, which is largely supplied by imports from outside the EU.

2.1.5 Biowaste

The EC defines biowaste as biodegradable garden and park waste, food and kitchen waste from households, offices, restaurants, wholesale, canteens, caterers and retail premises and comparable waste from food processing plants (EC, 2018b). Across the EU, between 118 million and 138 million tonnes of biowaste are generated annually (EC, 2010), of which an estimated 100 million tonnes are food waste (FUSIONS, 2015). Currently, only about 30 million tonnes (25 %) of this biowaste are selectively collected and recycled into high-quality compost and digestate (ECN, 2014). Current biowaste treatment processes are described in Section 4.3. However, the majority of biowaste still ends up in municipal waste, and goes to landfill or is incinerated.

Unmanaged biowaste poses a threat to public and environmental health, as it can attract insects, rodents and other disease vectors, and can generate leachate, which can contaminate surface water and groundwater (Reddy and Nandini, 2011). Moreover, when biowaste is disposed of in an uncontrolled way, it becomes a large source of methane emissions that contribute to climate change (Bogner et al., 2008). It was estimated that methane emissions from uncontrolled biowaste decay on fields or in landfill accounted for some 3 % of total EU greenhouse gas emissions in 1995 (EC, 2016).

2.2 The bioeconomy tomorrow

Innovation and market developments in the bioeconomy are rapidly evolving, especially in the areas of bioplastics and biocomposites, as reflected by the coverage of new technologies and bio-based products in the media. The focus of innovation is mainly on the replacement of fossil sources (commodity plastics), new or improved functions (composites), and biodegradability for applications such as soil cover in agriculture, or for high-volume applications including carrier bags and single-use packaging. In addition, research and development (R&D) efforts are increasingly geared towards the production of bioplastics from non-edible biomass and biowaste.

2.2.1 Biopolymers and biocomposites

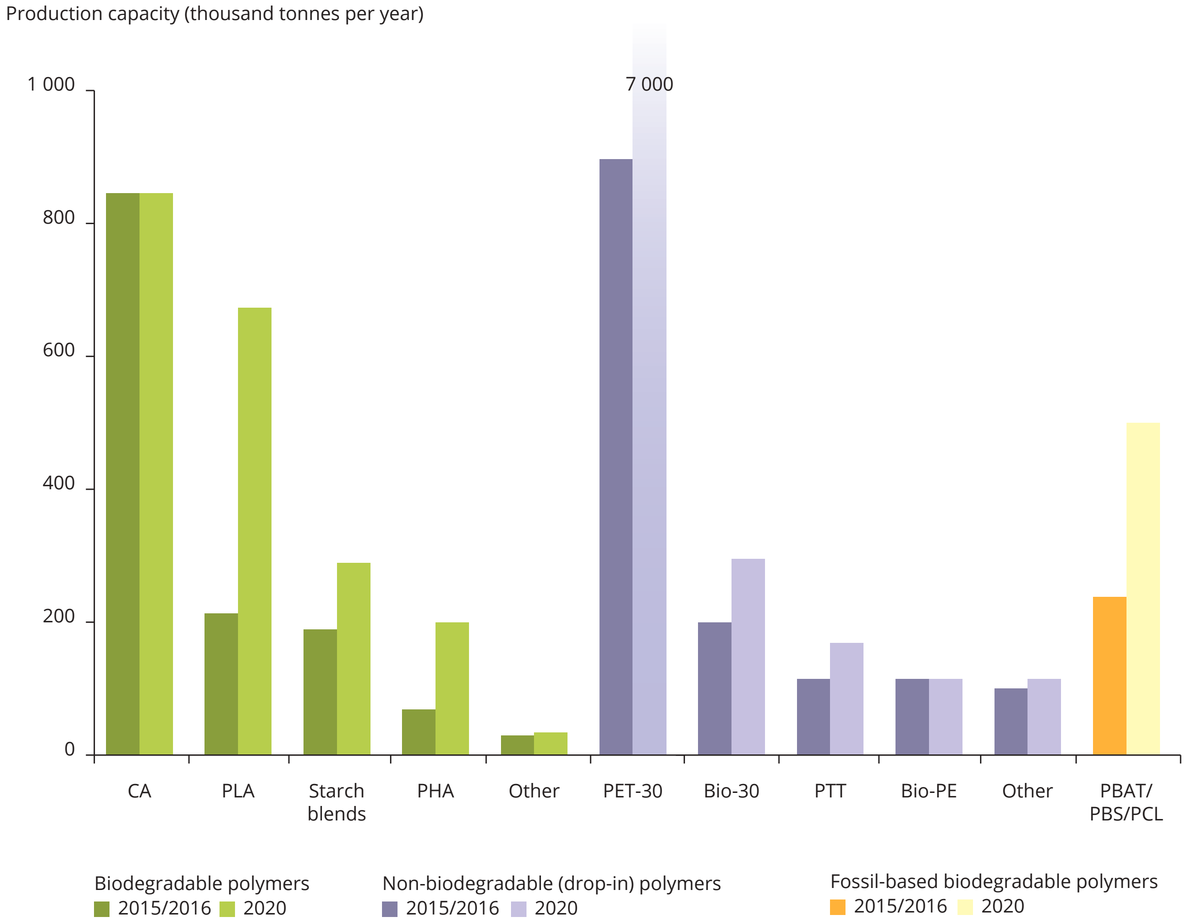
Worldwide biopolymer production capacity is forecast to increase from 6.6 million tonnes in 2016 to 8.5 million tonnes in 2021 (Aeschelmann and Carus, 2016). Europe's market share is likely to decrease slightly, from 27 % in 2016 to 25 % in 2021, while the Asian market is expected to grow from 43 % in 2016 to 45 % in 2021 (European Bioplastics, 2017). However, in 2019, more than 80 % of bioplastics are expected to be non-biodegradable (Giljum et al., 2016).

In the area of commodity plastics (e.g. PE, PET, PP), the largest growth in bioplastics is expected in drop-in polymers, such as bio-PE and bio-PET, mainly sourced from sugar cane and sugar beet. The removal of a maximum quota for the production of sugar beet in Europe in 2015 has opened opportunities for bio-based chemicals. It is also expected that the production of bio-based PLA, polyhydroxyalkanoate (PHA) and polyurethane (PUR) will increase (Figure 2.6).

The market for compostable and biodegradable plastic products could grow to beyond more than 300 000 tonnes in 2020, according to Kaeb et al. (2016). In addition to short-lived carrier and waste collection bags, functional products, such as barrier packaging (designed to be impermeable to gases, liquids or radiation) or products designed for outdoor use, are considered potential breakthrough markets for biodegradable plastics. The use of biocomposites is expected to grow further, as WPC and NFC granulates can be used in injection moulding for all kinds of technical applications and consumer goods, including in the automotive industry. An evolution towards bio-based polymers in combination with wood, cork and natural fibres is also likely, yielding materials applied in everything from toys to automotive interiors (Carus et al., 2015).

There are, however, still barriers that limit the market entry of bio-based alternatives to fossil-based products. Most importantly, oil is currently often a cheaper raw material than biomass. Furthermore, industrial-scale processing of biomass into products for end use is often more arduous than processing oil. Nevertheless, technologies for the manufacture of bio-based alternatives are developing rapidly, allowing greater resource and cost efficiency, as well as improved quality. At the same time, the legal framework and composting infrastructure have a critical impact on the development of the market for compostable plastics (Kaeb et al., 2016). There is ample scope for further policy actions by countries to address these aspects.

Figure 2.6 Global production capacity of bio-based biodegradable polymers, bio-based non-biodegradable (drop-in) polymers and fossil-based biodegradable polymers, 2015/2016 and 2020



Note: CA: cellulose acetate; PLA: polylactic acid or polylactide; PHA: polyhydroxyalkanoate; PET-30: polyethylene terephthalate; Bio-PE: biopolyethylene; PTT: polytrimethylene terephthalate; Bio-PA: biopolyamide; PBAT: poly(butylene adipate-co-terephthalate); PBS: polybutylene succinate; PCL: polycaprolactone.

Source: van den Oever et al., 2017; based on data from IfBB Hannover and European Bioplastics.

2.2.2 Wood-based materials

The evolution of the wood-based sector is quite stable, with the main challenge being the increasing demand for biomass for energy generation as a result of the European renewable energy policy. There is also a growing trend towards the further cross-linking of the wood-based value chain with other sectors, including those for bioplastics and textiles. Wood-based fibres, such as lignin, are the subject of (bio-)technological innovation in the search for non-edible and/or more sustainable biomass sources (Box 2.1).

2.2.3 New biomass sources and biorefining

Biorefining is the processing of many kinds of biomass into a spectrum of marketable products, such as food, feed, fibres, bulk and fine chemicals and fertilisers, and energy, including biofuels, power and heat, using biotechnology (IEA Bioenergy, 2014a). Currently, most existing biofuels and biochemicals are produced in single production chains, meaning that biomass resources, such as sugar, starch and oil crops, are in competition with the products of the food and feed industry (Cherubini, 2010).

Biorefining is an established system for producing everyday products such as beer, sugar, vegetable oils and wine (Box 2.2). At the same time, advanced biorefineries are being developed to process more diverse biological resources, including whole crops, forest-based resources and even marine algae (Section 4.1), into a wide range of platform chemicals that can be further processed into biocomposites, bioplastics, energy or food. As such, biorefining supports complex bio-based value chains rather than separate value chains for each biomass source and/or bioproduct. The global market for advanced biorefineries is less than 5 % of the conventional biorefinery market, but this share is expected to grow rapidly, since almost all current global investment is focused on increasing advanced biorefinery capacity (Rönnlund et al., 2014).

Fungal biomass is also attracting attention in the bioeconomy. The unique organic recycling capacity of fungi is being harnessed in industrial contexts. As such, fungal biomass could be the missing link between the recycling of biowaste and the production of food, for example growing mushrooms on waste coffee grounds (Rotterzwam, 2017), and the recycling of functional biomaterials in areas as diverse as packaging (Ecovative, 2017).

In summary, the rapidly evolving innovation landscape of biomaterials makes it very difficult to assess the macro-scale implications for biomass supply and demand related to the further upscaling and growth of the bioeconomy. At the same time, a complete replacement in Europe of fossil materials with bio-based alternatives is not expected in the coming decade.

Box 2.1 Clothes and carrier bags made from wood

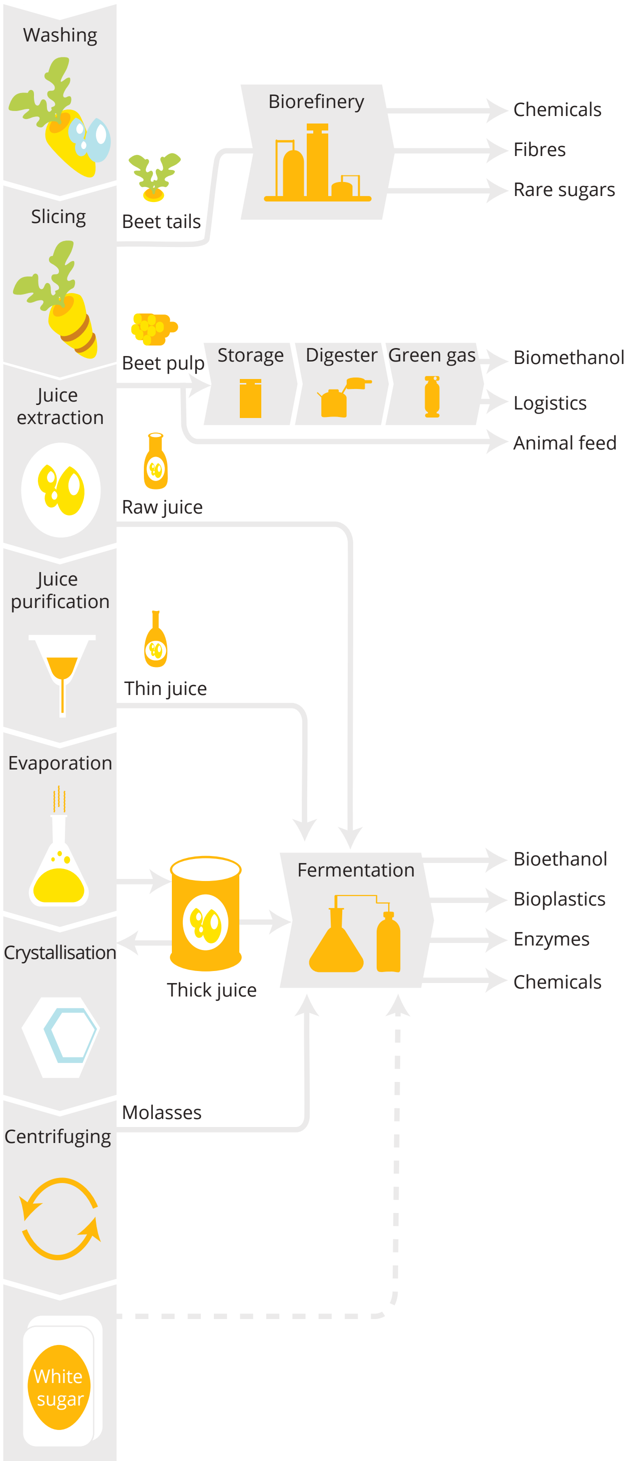
Paptic Ltd, a Finnish company founded in 2015, uses wood pulp to make bioplastic composite paper, combining the benefits of paper, plastics and textiles. The material is fully bio-based and recyclable in existing paper recycling facilities. As the material is made from wood pulp, its production can be integrated with a pulp mill or an integrated pulp and paper mill. Currently, the material is used for the production of carrier bags (Paptic, 2017).

Another Finnish start-up, Spinnova, wants to replace cotton as a source for textile yarn with wood pulp. Spinnova's technology converts wood fibres from pulp directly into yarn, without additional chemical treatment. The process, currently being piloted, appears to be a cost-competitive and environmentally benign alternative to cotton (Spinnova, 2017).

Box 2.2 A sugar biorefinery

Sugar beet is an important crop in north-west Europe, and the EU is the world's largest producer. The leaves are used as feed, while the sugar-containing roots are processed into thick sugar juice, through the processes of leaching, purification and evaporation. By a series of melting, centrifugation and crystallisation steps, refined white sugar is obtained, while the remaining syrup, or molasses, currently widely used in animal feed, can be used for the production of a wide range of products, such as ethanol, enzymes and chemicals (see Figure 2.7).

Figure 2.7 The production of sugar from sugar beet has several side-streams that can be biorefined into a multitude of other products



Source: EEA, 2018.

3 Towards a circular bioeconomy

Current data availability is insufficient to determine how circular the bioeconomy actually is. Nonetheless, even with today's limited knowledge, it is likely that improving the circular use of biomaterials would be beneficial to the sustainability of the bioeconomy. This chapter explores the associated challenges.

Key points ([5])

- The bioeconomy has substantial environmental impacts. The increasing global demand for food, feed, biomaterials and bioenergy resources could lead to exacerbating pressure on natural resources and demand/supply conflicts. This requires coordinated action and the careful consideration of trade-offs.
- Increased circularity would help to mitigate the environmental impacts of increasing demand for biomass by easing the competition between different biomass applications, reducing greenhouse gas emissions associated with material use and correcting geographical imbalances in nutrient flows.
- The possible greenhouse gas emission benefits of bio-based products compared with their fossil-based counterparts will depend on production practices, the lifetimes of the products and end-of-life treatment.
- A shift to agricultural practices that do not, or to a lesser extent, rely on chemical inputs could contribute to nutrient circularity (in the case of organic farming) and more efficient biomass production (in the case of precision farming).
- Approximately 72 % of the net annual increment of forests is currently harvested, pointing at a limited potential for the increased sourcing of wood biomass.
- By shifting to alternative (aquatic) sources of biomass and by using biowaste and residues more effectively, the resource base could be extended without the need for additional land for biomass production.
- Consumers can also contribute to sustainability, for example by eating less animal-based protein, preventing food waste and separating biowaste from other waste streams so that it can be (partly) converted to fertiliser by composting or digestion.
- Currently, the practices and policies for the bioeconomy and the circular economy are still loosely connected and more synergy could be created. Aspects that appear to be underrepresented are product and infrastructure design, and collaboration among the actors throughout the value chain.

3.1 Sustainability challenges

Biomaterial cycles should address the needs of current and future generations. Such needs include food, medicines, construction materials and chemicals, a wide range of consumer goods and energy. This inevitably leads to links with many other policy areas and issues: agriculture, biodiversity/natural capital/ecosystems, climate change, consumption patterns, food, forestry, energy, fisheries/aquaculture,

([5]) See body text for references.

soil, water and more. They all need to play their role in creating the right preconditions for the development of a sustainable circular bioeconomy.

Agriculture, forestry and fisheries have substantial impacts on soil, water and air quality, biodiversity and landscape amenity value (EEA, 2015a, 2017b). Practices that conserve natural ecosystems, biodiversity, soil fertility and water quality are an essential precondition for the production of sustainable bio-based products. Healthy ecosystems fulfil many vital functions and provide essential services for life on Earth. Apart from providing food, fibres and fuels, healthy ecosystems purify air and generate oxygen, regulate water flows, prevent floods, regulate global temperatures and form the engine for nutrient cycles and a reservoir for genes and species, supporting biodiversity. Healthy soils and oceans act as a global carbon sink, playing an important role in the potential slowing of climate change and its impacts.

The circular bioeconomy can help to mitigate the environmental impacts of resource use, but a systems approach that manages social, economic and environmental considerations together is required. For example, EU policies on water and the marine environment need to be integrated with those on climate change adaptation and biodiversity as well as socio-economic policies that either are or can be most damaging to healthy ecosystems: agriculture, energy, forestry, fisheries, tourism, transport, chemicals and certain industrial innovation policies.

First and foremost, increased circularity would help to tackle the tensions arising from the increasing demand for biomass as the bioeconomy grows: easing the competition between different biomass applications, sustainable yield increases and reducing the environmental impacts that biomass production exerts on ecosystems. Second, circular principles would also help to address negative externalities of the current bioeconomy by reducing the environmental impacts of biomaterial production and use, separating products that belong to the biological and technical cycles, and correcting geographical imbalances in nutrient flows.

Currently, the practices and policies for the bioeconomy and the circular economy are still only loosely connected, and more synergy could be created. Aspects that appear to be underrepresented are product and infrastructure design for the circular bioeconomy, and collaboration among the actors throughout the value chain (Antikainen et al., 2017).

3.2 Easing competition between different biomass applications

Competition between biomass utilisation for energy generation and food and feed production, or the material utilisation of wood, has been the subject of scientific and political debate (Rathmann et al., 2010; HLPE, 2013). Global population growth and rising living standards are associated with increasing levels of meat consumption and a rising demand for energy.

With global demand for food, feed, biomaterials and bioenergy resources expected to increase considerably in the near future (EEA, 2015b), competing uses for the same type of biomass (e.g. cereals for food, bioenergy or bioplastics) could lead to cross-market demand/supply conflicts, while biomass cultivation for different markets could bring about shifts in the land availability for food, biomaterial or bioenergy production — such as competition between the cultivation of maize for food and feed or for ethanol production (Majer et al., 2013). Shifting to diets that contain fewer meat, fish or dairy products could reduce pressures on the environment and/or open up opportunities for the production of biomaterials that could be used in construction and consumer goods, and to generate energy (Temme et al., 2013).

However, competition for biomass can also be seen as an incentive to promote the increasingly efficient use of available resources in a circular bioeconomy. For example, advanced biorefineries can process a wide range of biomass into a spectrum of marketable products and energy: food, feed, fibres, bulk and fine chemicals, fertilisers, biofuels, power and heat (IEA, 2007). By combining different products in a highly integrated production process, biomass can be used more effectively.

3.3 Increasing biomass production

Increasing demand for land-based biomaterials can be met by either increasing productivity (higher yields per hectare) or the expansion of the exploited land area. Higher productivity is usually associated with more resource-intensive cultivation (e.g. through higher water, pesticide and fertiliser inputs, and mechanisation) with associated impacts on the quality of soil, water and air, as well as biodiversity. On the other hand, expanding farmland and exploited forests occurs to the detriment of undisturbed natural areas, affecting biodiversity and carbon storage. Increasing terrestrial biomass production thus involves complex environmental trade-offs.

3.3.1 *Intensification of biomass production*

Between 1960 and 2010, the global production of primary crops almost tripled as a result of a combination of cropland expansion and yield increases. However, this rising trend has levelled off since 1990 (Grassini et al., 2013). Yields are no longer improving on 24-39 % of the most important cropland areas (Ray et al., 2012).

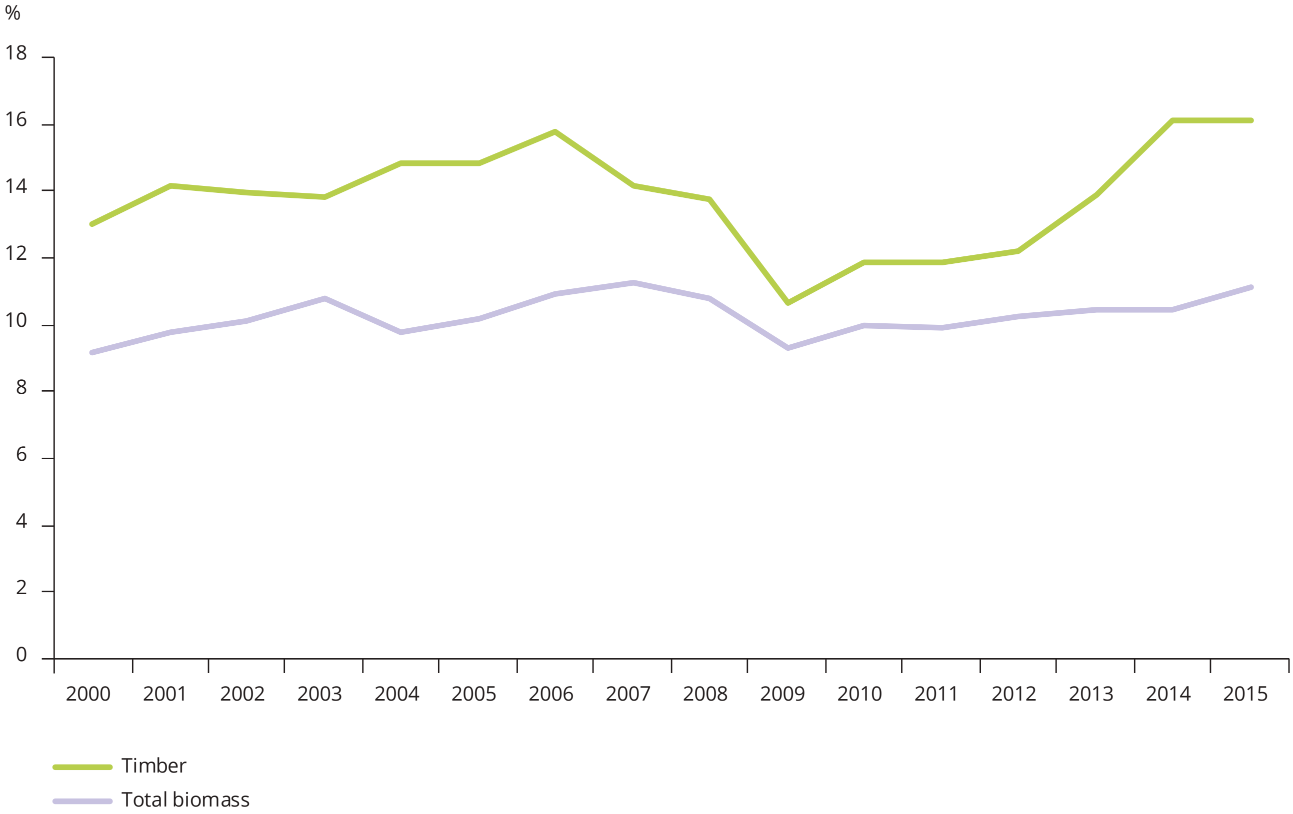
According to Ray et al. (2013), 'numerous studies have shown that feeding a more populated and more prosperous world will roughly require a doubling of agricultural production by 2050, translating to a 2.4 per cent rate of crop production growth per year'. The study finds that the top four global crops — maize, rice, soybean and wheat, which provide about two thirds of current harvested global crop calories — are currently well below this required threshold, with average yield improvements of only 0.9-1.6 % per year.

In the least developed regions, there is still potential for considerable yield increases, in particular in the least developed regions (Lobell et al., 2009; Neumann et al., 2010; Mueller et al., 2012; Dobermann and Nelson, 2013). In the EU, however, the potential for yield increases appears rather limited, as agriculture, on average, is already intensive with yields approaching their biophysical limit in many areas. In view of the associated environmental pressures, a shift to agricultural practices that do not, or to a lesser extent, rely on chemical inputs would appear to be more appropriate. Such a shift could contribute to nutrient circularity (in the case of organic farming) and more efficient biomass production (in the case of precision farming) (EEA, 2014).

3.3.2 *Expansion of the land area used for biomass production*

In addition to increasing yields, biomass production can be increased by the expansion of cropland and forest. Europe is becoming increasingly dependent on biomass sourced outside the EU to support its needs. Analysis of Eurostat material flow accounting data (Eurostat, 2017) shows that the proportion of biomass sourced outside the EU has increased over the past 15 years by 22 % and the proportion of imported timber increased by 23 % (Figure 3.1). Furthermore, the imported portion of Europe's total biomass material footprint of final

Figure 3.1 Import penetration of total biomass in the EU-28 (imported material as a proportion of domestic extraction + import - export)



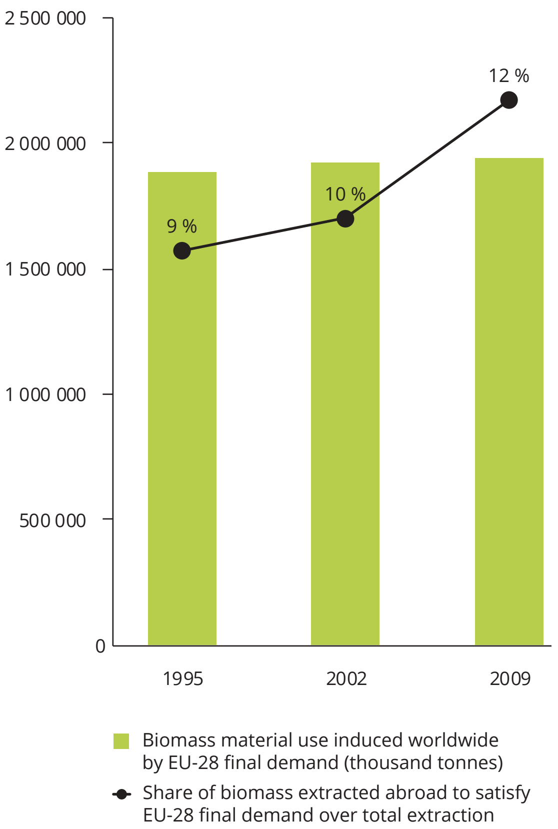
Source: Eurostat, 2017.

consumption increased by 33 % between 1995 and 2009 (Figure 3.2). This means that Europe is enlarging its claim on biological resources worldwide.

The types of crops produced for energy and material use — for example, rapeseed, soy and palm oil for biodiesel; maize and sugar cane for ethanol; cotton for clothing; and sugar and maize for bioplastics — are generally produced in monocultures on large-scale farms, which are increasingly located in tropical and sub-tropical regions (Smolker, 2008; Giljum et al., 2016). This type of bio-based production can have relatively substantial impacts on the environment (eutrophication, acidification, land use) compared with fossil fuel-based alternatives (JRC, 2017).

Wood-based resources are already heavily used, both for energy and for material production. Eurostat data for 2010 indicate that the net annual increment of forests in the EU-28 is estimated to be 720 million m³, and that 72 % of this net annual increment of forests was harvested (Eurostat, 2018b). Given this current harvest intensity, there appears to be limited potential for increased sourcing of timber within the EU if renewable energy targets are to be met primarily through bioenergy production (Mathijs, 2017). This points both to a conflict between energy and the material use of timber and to limitations within the EU for increasing timber harvests while preserving intact forest landscapes and biodiversity.

Figure 3.2 Biomass use in the EU, 1995-2009



Source: Timmer et al., 2015; based on WIOD data.

Future scenarios for energy could increase demand for forest biomass substantially, increasing the need for imports and, at the same time, exacerbating risks to sustainability such as land use change, biodiversity loss and the overexploitation of forestry reserves. For example, in Finland (UEF, 2018), the implications of increased wood harvesting both for bioenergy and for the production of wood-based materials are currently being studied (Heinonen et al., 2017), taking into consideration benefits from fossil-based materials substitution (Baul et al., 2017).

The EU could create opportunities to produce more bio-based products within the ecological limits of the planet by applying the principles of the circular economy to the bioeconomy, which would reduce the need for biomaterials. For example, by using biowaste (see Section 2.1) and residues as a feedstock for the production of bio-based products, the biomass resource base could be extended without the need for additional land for biomass production.

3.4 Shifting to alternative biomass sources and products

3.4.1 Aquatic biomass sourcing

The production of food, feed and bio-based products is currently largely reliant on agriculture and forestry. While marine resources have long been exploited for food, their use for the extraction of bio-based materials is a rather new development, certainly in comparison with terrestrial resources.

In the case of food, aquaculture may largely cater for the increasing demand for fish. Its proportion of production is rapidly increasing and is projected to cover an estimated 60 % of total demand by 2030 (World Bank, 2013). This expansion of the aquaculture sector is not without environmental challenges, which are rather similar to those faced in agriculture in relation to intensive livestock production. The demand for feed puts pressure on other (feedstock) species, and causes nutrient issues in coastal zones. Disease transfer to wild populations is also an associated risk (EEA, 2017b).

Marine organisms, such as microalgae, fish and invertebrates, are an important source of food and biochemicals. Recent advances in science and marine biotechnology have expanded the possibilities of marine biotechnology use (see also Section 4.1).

3.4.2 Replacing fossil-based products

One of the advantages that is often cited in connection with the bioeconomy is the replacement of non-renewable fossil-based materials with renewable biomaterials, which has a beneficial effect on carbon emissions and thus on climate change. Furthermore, when atmospheric carbon in the form of CO_2 is captured and stored in biomass and bio-based products, it no longer contributes to the greenhouse effect.

Compilations of available life-cycle analysis data by the Joint Research Centre (JRC, 2017) and the Ellen MacArthur Foundation indicate that bio-based products have the potential to outperform their fossil-based counterparts Figure 3.3) in terms of impacts on climate change. Nevertheless, even bio-based polymers contribute to fossil resource depletion, and several of them also have net greenhouse gas emissions.

Extending the lifetime of bio-based products and keeping the carbon in a closed cycle — a circular economy strategy — can maintain this positive effect. However, when the bio-based product is incinerated at the end of its useful life, the carbon re-enters the atmosphere as CO_2, contributing to the greenhouse effect. The contribution of bio-based products to climate mitigation will also depend on the way the land is used. For instance, converting forest to cropland can have an exacerbating impact on climate change. So, the possible benefits of replacing fossil-based products with bio-based products will depend on sustainable farming/forestry practices, extending the lifetime of the product and choosing sustainable options for end-of-life treatment.

Some biomaterials can lead to products that require less energy and/or cause less environmental harm to produce than the alternatives based on abiotic materials. The production of bio-based polyhydroxybutyrates (PHBs), for example, requires less energy than the production of petroleum-based plastics with similar characteristics, such as PP and high- and low-density polyethylene (HDPE and LDPE) (Momani, 2009).

New production technologies, including biotechnology and three-dimensional (3D) printing, can contribute to lowering the environmental impact of production processes. Integrated production processes, such as industrial symbiosis and biorefining, optimise the use of resources by starting from waste and side streams, processing them into a wide range of marketable products and eliminating waste.

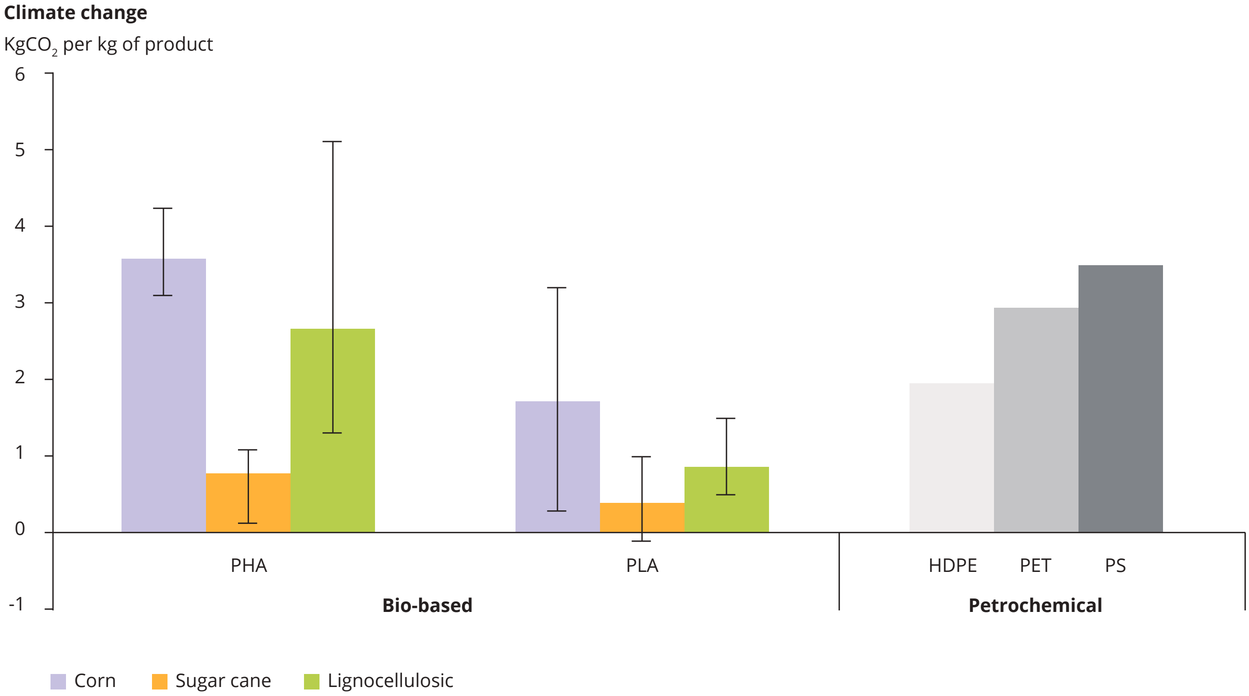
3.5 Keeping biological and technical materials separate

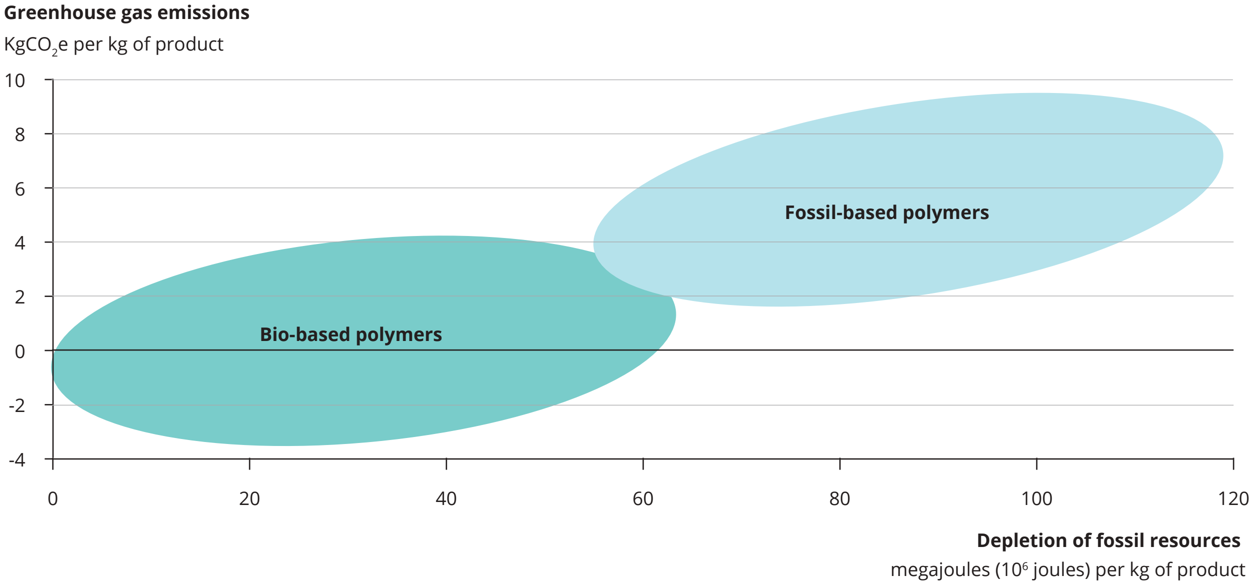
There is a popular understanding that a bioeconomy allows the regeneration of material resources because they are part of a biological cycle, which is inherently a closed loop; however, this is not how biological resources are currently used in material applications. For example, virtually all wood-based materials used today are either treated or mixed with technical materials during production processes. Construction wood is treated with chemicals, such as chromated copper arsenate and creosote, to render it resistant to insects, fungi and weathering; wooden furniture is made more durable by varnishes and coatings; and wooden toys are glued or painted, all of which makes them unsuitable for composting at the end of life. The separation at source of demolition wood from post-consumer wood from households is crucial for improving the quality of recycled waste wood, as there are limited possibilities to fully automate the sorting of mixed wood waste at a reasonable cost (Vis et al., 2016).

The same is true of non-biodegradable bioplastics, biocomposites and textiles, which currently cannot be safely returned to the natural environment to close the biological cycle. These biomaterials face the same end-of-life challenges as the technical materials they were intended to replace and, as a result, source separation, collection, sorting and recycling systems need to be put in place (Dahlbo et al., 2017). Moreover, recycling painted, coated or impregnated materials can be challenging, as the preservatives and glues are often regarded as contaminants that hamper future applications of the recycled materials. Even incineration for energy recovery is not always an option when toxic chemical substances are involved; as a result, some biomaterials end up in landfill.

Circular design strategies take the end-of-life fate of products into account from the very beginning of the product development process. The design of a product, including choices of materials and their combinations, connection types and overall set-up, has an enormous impact on its durability as well as its potential for repair, reuse, disassembly and recycling. Although strict separation is not always possible or necessary, ensuring that components belonging to either the technical or the biological cycle can be separated at end of life generally

Figure 3.3 Greenhouse gas emissions associated with different polymers





Fossil-based polymers include:
polypropylene (PP),
high-density polyethylene (HDPE),
low-density polyethylene (LDPE),
polyethylene terapthalate (PET),
polystyrene (PS),
polycarbonate (PC).

Bio-based polymers include:
bio-based polylactic acid (PLA),
bio-based polyhydroxyalkanoate (PHA),
bio-based polyethylene (PE).

Source: JRC, 2017 (upper panel); WEF et al., 2016 (lower panel).

makes it much easier to recycle both types of material sustainably.

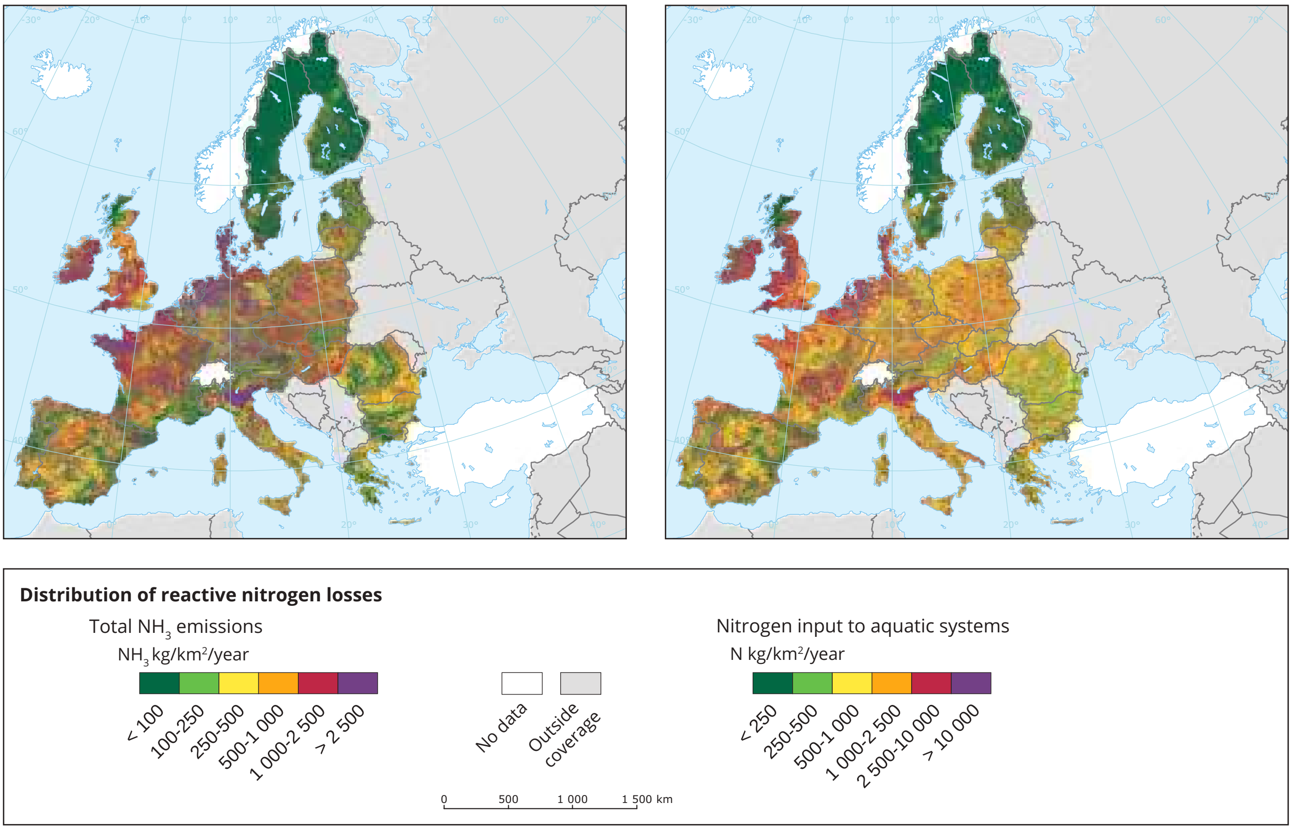
3.6 Improving nutrient and energy balance

In the globalised economy, food, wood and other types of biomass are traded across the planet. The geographical separation of the different stages of production, use and end-of-life treatment of biological resources creates imbalances in the biological cycle. While the circulation of carbon can be regarded as a dynamic global system, this is not true of nutrients such as nitrogen and phosphorus. Without adequate nutrient cycling, shortages are created near the source of biomass, and nutrient excesses can occur in ecosystems where the biomass is used or consumed. This has environmental and human-health impacts, as it can overwhelm the capacity of natural nutrient cycles to absorb these flows.

The lack of circularity for nutrients is exemplified by the fact that phosphate rock has been identified by the EC as a critical raw material, for which security of supply is at risk, economic importance is high and alternatives are not available. The lack of circularity for nutrients is exemplified by the fact that phosphate rock has been identified by the EC as a critical raw material in view of its high risk of supply (alternatives are not available) and high economic importance (EC, 2017a). It is principally used in the production of fertiliser, and demand is expected to grow in response to the need to feed a growing world population. Europe has only very limited amounts of phosphate rock and is largely dependent on imports from China, Morocco and the United States. Furthermore, there is only a small number of corporate producers, which adds to the supply risk (Phosphorus Platform, 2017). As a result, discussion about sustainable phosphorus management is high on the EU policy agenda, including measures to improve the efficiency of phosphorus use, recovery and recycling.

Nitrogen is not managed in a circular way either, and agricultural inputs increasingly depend on industrially manufactured nitrogenous fertilisers, synthesised from atmospheric nitrogen. Availability is thus not critical, but the environmental impacts certainly are. In Europe, the release of reactive nitrogen into the environment has more than tripled since 1900, affecting water and air quality, the greenhouse gas balance, ecosystems and biodiversity, and soil quality (Sutton et al., 2011). Figure 3.4 illustrates the geographical distribution of the release of nitrogen into the environment across Europe.

Figure 3.4 Distribution of reactive nitrogen release in the EU, 2000



Source: Westhoek et al., 2015.

Recent studies suggest that the majority of impacts related to nutrient flows have resulted from the expansion of the livestock sector (Sutton et al., 2011; Leip et al., 2014; Buckwell and Nadeu, 2016), which has been accompanied by an increase in imports of livestock feed. Most of the nutrients contained in biomass end up in manure, which cannot be adequately returned to the soil in Europe.

Keeping the nutrient balance in equilibrium in the global production and trade systems is challenging. An efficient nutrient cycle is, however, a major issue for a sustainable circular bioeconomy. Nutrient shortages reduce soil fertility and impede healthy plant growth, while nutrient excesses cause environmental problems as a result of evaporation to the air or releases to groundwater and surface water. Innovative and productive low-input systems, using organic and precision farming techniques, can help improve the nutrient balance and reduce nitrous oxide emissions related to fertiliser use.

The environmental impact of the use of biomaterials is also influenced by the energy balance of the production systems and the distance between the places of production and consumption. Shorter distances reduce transport emissions, which may compensate for any productivity penalties of local production. They may enable more circular flows of materials and nutrients. In this way, introducing circular economy principles into the bioeconomy can help to create business and distribution models that make use of more locally organised biocycles and locally available biomaterials, while preventing the loss of valuable materials.

3.7 Changing consumer behaviour

Consumers can also play a role in creating a more sustainable bioeconomy, for example by eating less animal-based protein, preventing food waste and separating biowaste from other waste streams so that it can be (partly) converted to fertiliser by composting or digestion.

The environmental and health impacts of the consumption of meat in Europe requires re-evaluation (Foley et al., 2011; McMichael et al., 2007). Diets in the EU have changed considerably, but total animal protein consumption per person remained relatively stable from 2000 to 2013. The consumption of poultry meat, cheese, fish and seafood has increased at the expense of beef. The implications in relation to biomass and the net environmental impacts of these changes are difficult to assess, because of the contrasting carbon footprints and varying nutrient and (agri-)chemical emissions associated with the different food categories (EEA, 2017b).

Product lifetime extension strategies depend not only on the decisions made and actions taken by producers and retailers, but also on consumer attitude and behaviour. The reuse, repair and remanufacturing of bio-based products contribute to greenhouse gas mitigation, as biomass can be used as a (temporary) carbon sink. The bioeconomy and the circular economy have a common agenda in this regard and can reinforce each other to find better ways of and technologies for reusing and encouraging secondary material flows.

4 Promising practices

This chapter provides some examples of innovative biomaterial applications that can contribute to the transition to a circular bioeconomy. Data on full life-cycle assessments of the products involved are not available, and so the environmental benefits of upscaling these niche activities have not been quantified. As with any societal transition, no specific case can cover all aspects. The challenge of integrating different innovations (both technical and social) to create system change is discussed in Chapter 5.

Key points ([6]):

- Biorefinery plants can efficiently deliver a variety of bio-based raw materials. The contribution to the circular bioeconomy is particularly high where second-generation feedstock is used.
- 3D printing with bio-based and biodegradable plastics is promising, but proper discarding mechanisms need to be put in place.
- Multipurpose crops, such as hemp, can increase the efficiency of land use and biomass production. Valorising production residues also has potential, but increasing the economic use of crop and tree residues carries the risk of soil depletion.
- Biowaste treatment is another key strategy. Combining anaerobic digestion and composting improves the performance of both processes. The composting or digestion of biowaste requires a stringent selective collection at source to eliminate the cost of separating plastics or other contaminants.
- About 88 million tonnes of food per year are currently wasted in the EU. Reducing such waste requires increased production efficiency and innovation, for example by finding uses for unavoidable food waste such as peel and kernels, as well as increased consumer awareness and corresponding changes in behaviour.
- The lifespan extension of bio-based products is just as valid as it is for technical products. Material durability is a particular challenge in this respect, as treatment with preservative technical materials hampers recycling. This can be prevented through conscious material choice for particular applications.
- Renew and repair schemes for durable bio-based products, such as furniture, are still an exception. Their effect on material demand will in any case largely depend on consumer response and rebound effects.
- The cascading use of biomass is a core strategy for maintaining the value of biomass for as long as possible, before sending it to energy recovery. The potential for cascading is greatest in the wood sector, although the concept can be broadened to natural fibres, such as cotton, hemp, jute and sisal, as well as bioplastics.

([6]) See body text for references.

4.1 New materials and production methods

The EU bioeconomy innovation agenda puts great emphasis on new biomaterials — mainly biochemicals and bioplastics — as well as on developing processing pathways for the conversion of biomass into those biomaterials. Integrating these innovations into the logic of a circular economy model would result in considerable sustainability improvements.

Bioplastics could make a significant contribution to a sustainable and circular bioeconomy if their specific properties were exploited in better ways. The key to getting more out of bioplastics in the circular economy is to use the most appropriate bioplastic for any given application (Box 4.1).

Achieving the greatest possible level of environmental benefit from bioplastics is also linked to appropriate end-of-life management. Non-biodegradable bioplastics, such as bio-PET, face the same end-of-life challenges as conventional plastics: they need to be appropriately collected and recycled in order to prevent resource loss and CO_2 emissions, and to prevent land and marine pollution. The use of such bio-based plastics on an industrial scale should thus be linked to innovation and regulation efforts to improve the collection, reuse and recycling of plastics.

Compostable or biodegradable material litter is not desirable either, as compostable materials are designed to decompose under controlled circumstances in industrial composting facilities and biodegradable materials decompose in a specific medium (water, soil or air). If the materials do not decompose fully in natural ecosystems, the littering of such materials is generally more detrimental to the environment than collection and proper waste treatment.

Plastic bags that can be composted in industrial installations are not always easy to distinguish from conventional ones, adding to the risk that non-degradable plastics will contaminate the composting process. To prevent this, sieves are installed at the entrance of composting installations to prevent plastics and other bulky waste from entering the process. As a result, compostable plastics are sieved off and sent for incineration along with the non-compostable materials. The challenge here is to align the use of biodegradable plastics with the context in which they will be applied, as well as with the context in which they will end up after use.

A further challenge is the availability of biological resources. A study by European Bioplastics (2016) estimated that the land required to grow the feedstock for the worldwide production of bioplastics was about 0.68 million hectares in 2014 and is

Box 4.1 New biomaterials

Compostable snack bar wrappers from potato waste

Rodenburg Biopolymers is a Dutch pioneer in the area of bioplastics. With decades of experience in turning waste from the potato-processing industry into cattle feed, it has been looking to convert the remaining potato starch waste into a new bioplastic. The result of the company's research is Solanyl, a food-grade polymer film compound that is compostable. The energy used in its production is only one third of that needed for the production of fossil alternatives such as PP. In late 2015, Mars began using this material for snack bars wrappers (Laird, 2016).

Biomaterials for cars

In the automotive sector, material durability is a critical parameter when making design choices. For example, car manufacturer Ford has a research programme aimed at testing and applying biomaterials for different automotive applications. Some examples that are being investigated are soy-based PUR foam for car seats, wheat straw as a structural filler for injection moulding plastics and PLA as a bio-based resin for interiors. Results show that the biodegradation rate of PLA is too high for current product requirements, but that wheat straw-filled PP can be successfully used in car interior parts, offsetting 13 tonnes of CO_2 emissions per year (Lee, 2013). However, the potential influence of adding bio-based fillers on the recyclability of PP has not been reported. In this case, focusing on the recycling of conventional PP could be a more sustainable alternative than looking for bio-based alternatives for existing talc or glass fillers.

Other examples include a material called Sulapac, produced by the Finnish company Paptic Ltd (see Box 2.1), a fully biodegradable packaging material made from renewable and sustainable raw materials. Wood from sustainably managed Nordic forests is used. It contains no harmful components, has a low carbon footprint and can be processed in the same way as plastic (Sulapac, 2018).

expected to increase to 1.4 million hectares by 2019, about 0.02 % of the world's agricultural land (van den Oever et al., 2017). If all fossil-based plastics production were to be converted into bioplastics production, the required biomass volume would be about 5 % of the total amount of biomass produced and harvested each year.

However, as bioeconomy research is increasingly focused on alternative feedstocks from waste, byproducts and residues from agriculture, the future land requirements are expected to be lower (Van Wijk and Van Wijk, 2015). Moreover, the current use of agricultural biomass for biofuels is 20 times higher than for bioplastics (Section 2.1). Additional pressure on demand for agricultural biomass from bioplastics could thus be prevented if bioethanol were to be used in the production of bioplastics instead of being directly used as fuel.

4.1.1 Biorefinery: producing more products from fewer resources

Biorefinery plants process a variety of bio-based raw materials, side streams and waste in highly integrated and resource-efficient processes. As such, they provide the opportunity for joining bio- and circular economy principles, especially when using second-generation feedstocks from outside the food and feed sector, including materials such as wood and grass, harvest residues and biowaste (Section 2.2).

Recently, R&D efforts have focused on the use of microalgae as a third-generation feedstock for biorefining. Microalgae have multiple advantages. As plants they remove CO_2 from the atmosphere, while containing a much higher lipid content by weight than other plants. Moreover, algae can be produced on non-arable land, in seawater or in waste water. This reduces freshwater consumption and eliminates competition with food production, which adds to the environmental sustainability of this feedstock (Trivedi et al., 2015). Algal biomass can be processed into a variety of chemicals and polymers, biofuels, food and feed ingredients as well as bioactive compounds — antibiotics, antioxidants and metabolites (Ben-Hamadou, 2017). Aquatic biorefining is another example of a function of advanced biorefineries with the potential to contribute to a circular bioeconomy (Box 4.2).

Different biorefinery plants can also exchange biomaterial flows whereby the residue from one bioindustry becomes an input for another industry, giving rise to so called symbiosis networks, that is, integrated clusters of bioprocessing plants, located close to one another and working together. In such biorefinery clusters, biomass resources can be fully used locally in a variety of products and energy carriers,

Box 4.2 Aquatic biorefinery

An aquatic biorefinery is based on aquaculture and includes marine, freshwater and dryland fisheries, and the algae industry. In addition to producing resources for the food and feed industries, aquaculture can also provide aquatic biomass for other industries and end uses, such as the production of biofuels, chemicals and nutrients and the extraction of dietary supplements, such as omega-3 oils, from fish waste and algae.

Nutrient recycling can be supported by converting residues and organic waste from aquaculture into biogas and agricultural fertilisers. The biogas can then be transformed into biofuels, power or heat, for example to heat a nearby greenhouse. This way, an industrial symbiosis cluster can be organised around aquaculture, so that all raw materials are fully used in a wide variety of products.

For many value chains in an aquatic biorefinery, it is essential that the aquatic feedstock harvesting and the biorefining installations are located close to one another, as the raw materials need to be fresh when processed. This means that aquaculture biorefineries have a positive effect on local job creation.

Sybimar is a Finnish SME producing fish in specially constructed inland fish farms (Figure 4.1). In addition to fish for the food industry, Sybimar also produces biogas from fish waste and food industry side streams for the generation of biofuels, power and heat. In addition to biogas production, Sybimar is synergistically connected to greenhouse farming. In this way, Sybimar meets part of its own electricity and heat demands, while also taking care of its own waste treatment. Nutrients, water, waste heat and CO_2 are recycled back into the production process (Rönnlund et al., 2014; Sybimar, 2017).

while reducing the need for transport and eliminating waste (EU, 2015).

Several advanced biorefinery pilot plants are being set up, such as the Domsjö plant in Örnsköldsvik, Sweden, a demonstration plant for transforming wood or straw into sugars and lignin and the further fermentation of the sugars into chemicals (SEKAB, 2017). Another example is the Bio Base Europe pilot plant in Ghent, Belgium, which offers services related to laboratory-scale process development and optimisation, as well as upscaling to production levels and custom manufacturing of a broad range of biorefinery processes and feedstocks (BBEU, 2017).

Key challenges and barriers for biorefineries include high levels of initial capital investment, high transport costs in relation to biomass, and the considerable variability of biomass composition and supply throughout the year. The high levels of capital investment can be supported by maximising the added value of the resulting products, for example by producing at least one high-value chemical/material product, as well as low-grade and high-volume products such as animal feed, fertilisers and heat.

The compositional variety in biomass feedstocks is both an advantage and a disadvantage. Advantages are that biorefineries can make more product types than petroleum refineries and that they can make use of a wider range of raw materials. A disadvantage is that a larger range of processing technologies is needed to accomplish the necessary conversions, and most of these technologies are still at a precommercial stage (Cherubini, 2010).

4.1.2 3D printing with biomaterials

Additive manufacturing, also known as 3D printing, is often mentioned as a revolutionary development in the field of resource-efficient production. In principle, virtually any product can be printed, and biomaterials can serve as feedstocks. Research on 3D printing using biomaterials is mostly focused on medical applications, such as the production of implants, scaffolds for tissue engineering and drug delivery systems, based on the printing of living cells (Chia and Wu, 2015). However, the technology can also make use of bio-based or biodegradable plastics such as PLA, replacing conventional plastics, mainly acrylonitrile butadiene styrene (ABS).

The combination of 3D printing with bio-based and/or biodegradable plastics, reliant on the local sourcing of biowaste or residues, holds promise for playing a central role in a circular bioeconomy. End-of-life considerations for the printed products, however, need to be taken into account, for example by ensuring that locally produced renewable resources are effectively recycled after use. The sustainability of energy for the printing process also needs to be considered, for example by using renewable energy (Van Wijk et al., 2015).

Both virgin and recycled plastics can be used in 3D printing. Life-cycle analysis results indicate that, in both cases, using 3D printing in the car interior spare part business, rather than factory-made spare parts, could reduce environmental impacts. However, the quality issues of recycled plastics currently present a challenge for implementation (TURKU, 2017).

4.2 Multipurpose crops and valorising residues

The value chains, from biomass production through bio-based building-block processing to application in products, are becoming more intertwined: for example, wood-based biomass finds its way to clothing, while flax fibres end up in cars and insect-based chitin is used in cosmetics. Two specific strategies can improve the sustainability of the bioeconomy in the production stage: the use of multipurpose crops and the valorisation of production residues.

Hemp is an example of a multipurpose crop, delivering fibre, seeds, pharmaceuticals and woody by-products (European Industrial Hemp Association, 2017). Crucial to the sustainable cultivation and use of multipurpose crops is the development of an integrated approach to production and refining that ensures optimal use of the different plant parts for food, feed, materials and energy generation. At the same time, the conditions for sustainable production need to be taken into account. Finally, the location of crop production should be as close to the refineries and end markets as possible in order to reduce the transport-related greenhouse gas emissions.

The Libbio Horizon2020 research project is an example of such an integrated approach. It aims to develop and optimise a breeding and cropping programme for Andean lupin (*Lupinus mutabilis*) on marginal land, install primary processing pipelines and develop high value-added consumer and business-to-business products in the areas of food, feed, materials and bioenergy (Libbio, 2017).

Even before bio-based products enter the market, considerable amounts of biomass residues are lost.

The volume of production residues available is far greater than the volume of consumption-generated. For example, in 2010, there was approximately 52 million m³ of post-consumer wood waste, of which some 36 million m³ were recovered. This was smaller than the volume of forestry residues and production waste, which amounted to approximately 178.7 million m³ (Vis et al., 2016).

Within agriculture, more than half the globally harvested dry mass consists of agricultural residues and inedible biomass, such as cereal and legume straw; shoots of tuber, oil and sugar; vegetable crop stalks, leaves and shoots; and fruit and nut tree prunings and litter. It is estimated that 121 million tonnes of agricultural crop residues (mainly straw) could be generated annually in Europe, together with 46 million tonnes of forestry residues and 31 million tonnes of grass (Iqbal et al., 2016).

Historically, crop residues have been used in many ways. They are an important source of household building materials and fuel in many low-income countries and they provide bedding and feed for animals. They also offer an excellent substrate for the cultivation of mushrooms, are used for making paper and are an important source from which organic compounds, such as pharmaceuticals, are extracted. There remains, however, scope for the use of excess biomass residues for producing high-quality animal and fungal protein or fibre at both the local and regional levels (Smil, 1999). Moreover, the use of agricultural or even fishery residues as a resource for materials could create economic value by extending the biomass resource base (Box 4.3).

A major barrier to increasing the use of agricultural and forestry residues is the cost associated with harvest logistics, which is often higher than that for primary fossil materials. Local biorefining systems that match residue supply and material demand in a smart way need to be developed, as the wide dispersal of residues does not fit the economies of scale of the existing industrial oil-based production system.

Increasing the economic use of crop and tree residues carries the risk of depleting the quality of ecosystems if too many residues are taken. Plant residues may seem valueless when they are left on the field or in the soil, but they contribute substantially to the stability of the biomass production system. They provide protection against water and wind erosion, increase the capacity of soil to store water, provide soils with organic matter and recycle nutrients (Smil, 1999).

Initiatives to increase the removal of plant residues for economic use, whether the result of policy stimuli, research and innovation or large-scale implementation, should monitor the production systems from which the residues are sourced and take appropriate measures to safeguard ecosystem quality. Furthermore, the absence of a supportive harmonised forest policy within the EU is seen as a barrier to increasing the sustainable sourcing of forest biomass residues (Iqbal et al., 2016).

Box 4.3 Residue-based products

Piñatex — creating textiles from pineapple residues

The company Ananas Anam has developed an innovative non-woven textile called Piñatex™, made from pineapple leaf fibres. These fibres are the by-product of the pineapple harvest, meaning that no extra land, water, fertilisers or pesticides are required to produce them. The original development was carried out in the Philippines, with finishing, research and continuing development now being undertaken in Spain and the United Kingdom. Piñatex provides additional income for farmers, while creating a new industry for pineapple-growing countries (Ananas Anam, 2017).

Packaging from tomato fibres

Solidus Solutions (the Netherlands) has developed a new packaging material based on tomato fibres. The leaf and stems from the tomato plant, which are leftovers from the harvest, are crushed and mixed with fibres of recycled paper, producing a type of cardboard for use as packaging. This packaging is used by some tomato producers, including Canada's Pure Hothouse Foods and France's Idyl (Solidus Solutions, 2017).

Shell-based cosmetics

Chitin is extracted from the shell of crustaceans, insects and fungi. It is transformed to the sugar chitosan, which is used for medical purposes (to treat obesity, high cholesterol, and Crohn's disease), in cosmetics, nutritional supplements, packaging foils and antibacterial coatings (Ravi Kumar, 2000).

4.3 Biowaste treatment

Biowaste represents a large volume of biomass (see Section 2.1) that can be used for new applications as well as for the replenishment of nutrients in biomass production systems. In a circular bioeconomy, the recycling of biowaste is a crucial strategy for optimising the use of the available biomass resource base.

4.3.1 Composting and anaerobic digestion

The efficient composting of biowaste prevents greenhouse gas emissions resulting from decay and provides a natural soil additive that acts as a carbon sink and nutrient source. Using compost on soil not only improves its structure, but also replaces the need for some chemical-based fertilisers, the production of which is very energy intensive.

Another, often complementary biowaste treatment is anaerobic digestion, a process in which biowaste is converted by microorganisms into biogas and digestate (Figure 4.1). The biogas, a mixture of CO_2, methane and other trace gases, can be used for energy production or as a base chemical. The digestate, rich in nutrients and organic matter, can be used as a plant fertiliser, thus replacing industrially produced mineral fertiliser.

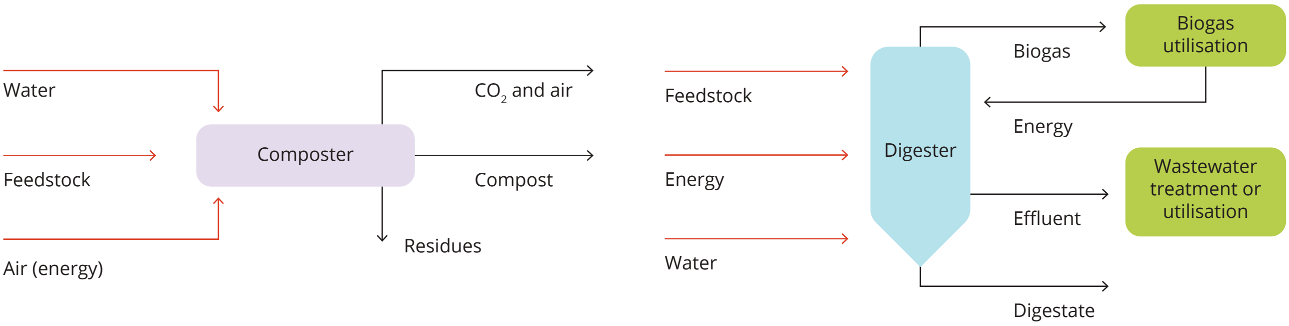
The available feedstock largely determines the efficacy of composting or digestion. Garden waste, which typically has a large proportion of lignocellulosic materials, has a low biogas yield (30 m^3 per tonne) and thus is more suitable for composting, while food waste yields more than three times more biogas per tonne and digests more rapidly and completely in a digester (Kraemer and Gamble, 2014).

However, when combining anaerobic digestion and composting in an integrated system, synergies that improve the performance of both processes can be achieved. In an integrated system, the anaerobically obtained digestate is further composted. This diminishes odor generation and allows obtaining a more homogeneous output with higher moisture content. The amount of waste generated is also lower in such a combined process, as the waste streams from the digestion process serve as feedstock for the composter (Figure 4.2). As the material has already been decomposed during digestion, it is easier to convert into compost, which reduces throughput time by about 40 %. It also reduces the overall operating costs. If well balanced, the digester effluent water can supply the water required for composting, which eliminates the need for effluent treatment. Biogas from the digester can provide electricity directly to the composter, without going through an external power grid (Kraemer and Gamble, 2014).

Restrictions on manure application in areas with high nutrient levels or livestock densities, along with concerns about global phosphorus depletion, have increased the attention paid to efficient nutrient management, including efforts to recover nutrients from manure and biowaste streams. Through a variety of techniques, including membrane filtration, evaporation, ion exchange and precipitation, the nutrients present in digestate can be concentrated or extracted in mineral form and transformed into marketable biofertiliser (IEA, 2015).

The successful composting or digestion of biowaste requires the separate source collection of biowaste to eliminate the cost of separating plastics or other contaminants that would affect the quality and

Figure 4.1 Composting and anaerobic digestion



Source: Kraemer and Gamble, 2014.

Box 4.4 Examples of biowaste digestion

In Noorderhoek in Sneek (the Netherlands), sewage water and organic waste from an apartment building are treated in an anaerobic digester. The resulting biogas is used to heat the building, while at the same time phosphorus is recovered from the digestate; nitrogen is not recovered, as its concentration is too low for efficient recovery. Instead, it is converted into gaseous nitrogen (N_2), so it can be safely released into the atmosphere. Research is still ongoing into how to recover the nitrogen by means of growing algae, which can be used as a fertiliser or for bio-oil production. One element of concern when considering reuse is traces of medicines and cosmetics in sewage water (van Kasteren, 2012).

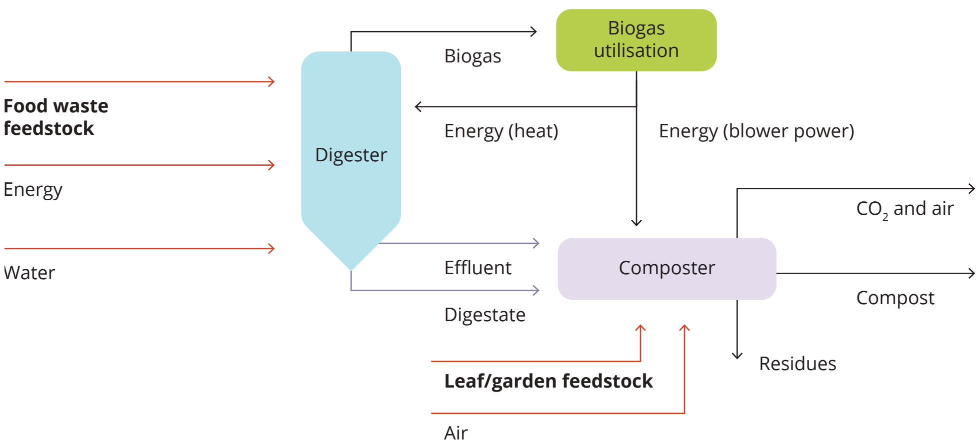
Several new integrated anaerobic digestion and composting plants have been set up in recent years or are planned for the future. The Acea Pinerolese plant (Pinerolo, Italy) is a biowaste treatment facility based on the integration of aerobic and anaerobic digestion processes. The plant consists of four sections: two for solid biowaste treatment by aerobic and anaerobic digestion, a section for waste water treatment and a landfill area equipped for biogas collection. The four sections are interconnected to maximise biogas yield and compost production, minimising landfill. Biogas production at the facility exceeds the plant's own energy consumption, generating a net yield of electricity for the grid and for heat, which is used in nearby residential areas (Morone et al., 2017). Operational costs are covered by, in almost equal parts, tipping fees and sales of the derived power and heat. Work has also started for turning the plant into a biorefinery producing biogas and added-value chemicals, based on compost hydrolysate for use in fertilisers; the new biorefinery process is planned to start in July 2018 (Montoneri and Mainero, 2016).

In Beerse (Belgium), the intermunicipality waste management company IOK processes about 35 000 tonnes of vegetable, fruit and garden waste per year in their composting plant. From November 2018, the composting installation will be integrated with a pretreatment digester in order to produce 400 m^3 of biogas per hour. Around 75 % of the gas will be used to drive a heat power plant to power the treatment site and the remaining 25 % will partly be used to provide energy to some nearby buildings and partly undergo membrane filtration to produce biomethane, a natural gas. This biomethane can then be integrated into the gas system. The digestate from the plant will be processed into compost in the existing composting installation (Van Gorp, 2016).

safety of the resulting compost or digestate. Large differences exist in the provision of separate collection and treatment capacity for biowaste across Europe (Figure 4.3). A survey by the European Compost Network (ECN) showed that in 2014 about 30 million tonnes of biowaste was separately collected and composted or digested in about 3 500 treatment plants across Europe. More than 90 % of collected biowaste is composted (ECN, 2016).

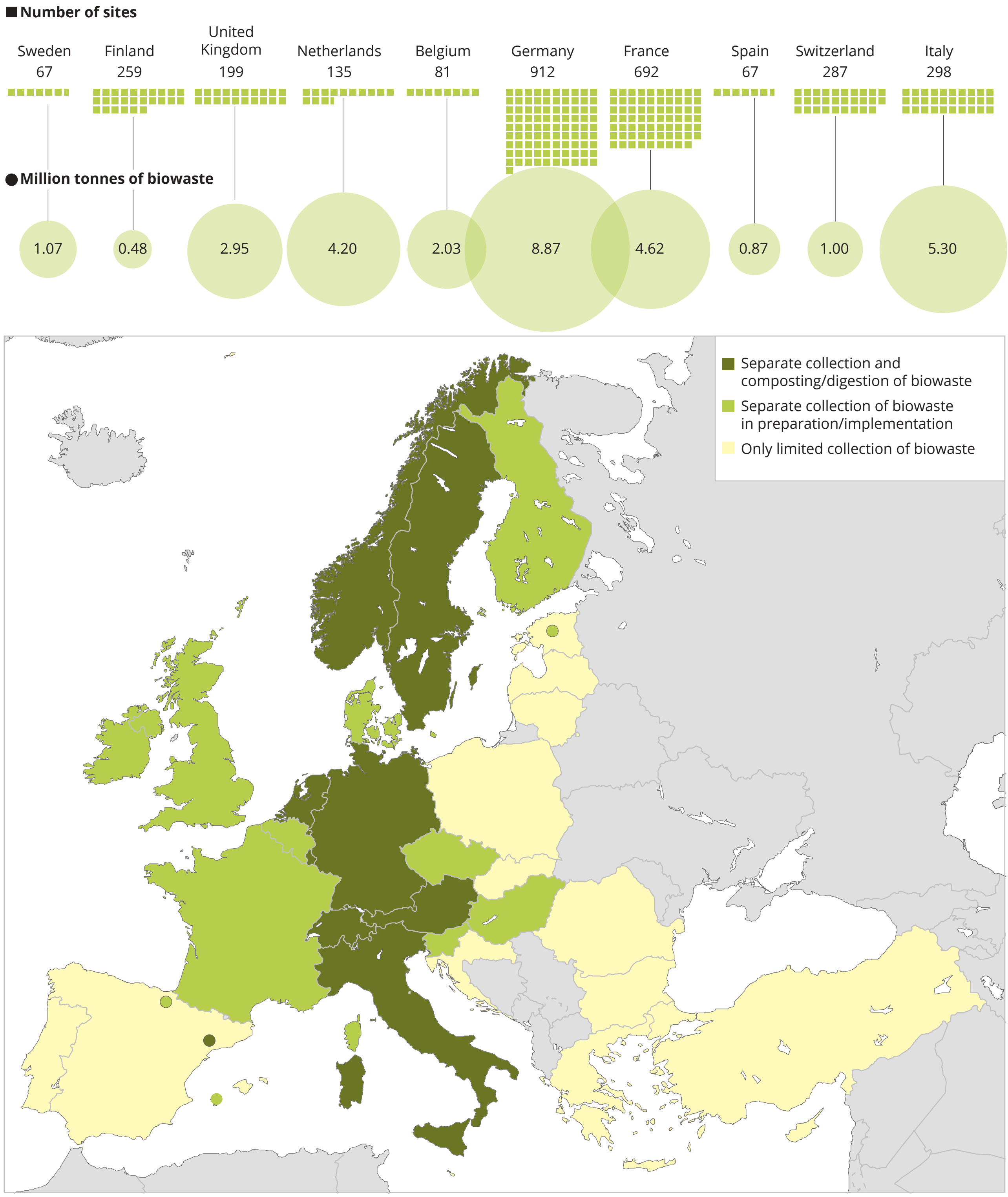
A main barrier to the upscaling of compost and digestate production in Europe is the current limited demand from agriculture. This is caused by a combination of the low market price of synthetic fertiliser, a lack of awareness among farmers about the potential of compost and digestate, and the limitations imposed by the regulatory frameworks on food safety and nitrate pollution (Gillabel et al., 2012).

Figure 4.2 Inputs and outputs for integrated anaerobic digestion and composting systems



Source: Kraemer and Gamble, 2014.

Figure 4.3 Separate collection of biowaste in Europe



Source: ECN, 2016.

4.3.2 Reducing and valorising food waste

For environmental, economic and social reasons, reducing food waste is a priority of the circular economy strategy. The EU is committed to meeting the United Nations (UN) target of halving per capita food waste at the retail and consumer levels, and reducing food losses along production and supply chains (EC, 2015a). In line with the target set by the United Nation General Assembly as part of the 2030 Sustainable Development Goals, the EC is committed to halve per capita food waste at the retail and consumer level by 2030, and to reduce food losses along production and supply chains (EC, 2015a). This requires an increase in efficiency and innovation across the value chain, for example by using unavoidable food waste such as peel and kernels, as well as increased consumer awareness.

Statistical information on waste generated along the value chain is limited because of the lack of a specific category 'food waste' in official waste statistics. Based on 2012 statistics, the EU's Seventh Framework Programme for Research and Technological Development (FP7) project Fusions estimated that the EU loses and wastes around 88 million tonnes of food per year, mostly in the distribution and consumption stages (Table 4.1).

In 2015, the Food and Agriculture Organization of the United Nations (FAO) quantified the global carbon footprint of food waste at around 4.4 billion tonnes of CO_2 equivalent per year (FAO, 2015). For Europe, the FP7 Fusions project estimated emissions related to food waste at 227-304 million tonnes of CO_2 equivalent in 2011 (Vittuari et al., 2016).

Furthermore, a UK study indicated that about 77 % of total food waste in the United Kingdom in 2015 was avoidable or possibly avoidable (Quested and Perry, 2017). The FAO (2013) estimated that the economic cost of global food waste in 2007 was about USD 750 billion on the global scale. The total estimated monetary value of food waste in the EU (all phases) amounted to around EUR 144 billion in 2009, of which around EUR 92 billion was lost at the consumer stage (Zoboli, 2015). For many EU countries, losses are equivalent to 0.5-1 % of gross domestic product (GDP).

In the case of unavoidable food waste, the EU's goal is to develop options for reuse, and many food-processing companies see it as a way of increasing their profitability, as it can decrease the costs of waste treatment and also pave the way for the development of innovative ingredients and food products. The most promising sources of valuable compounds from fruit and vegetables are olives, exotic fruit and tomatoes, which can provide several valuable compounds, including antioxidants, fibre, phenols, polyphenols and carotenoids (Mirabella et al., 2013). To reuse biowaste for new applications, justify the investment in R&D and cover the costs of additional processing steps, it is essential that valuable and high-added-value products are made (Mirabella et al., 2013).

4.4 Product and material lifespans

Extending the lifetime of products and materials is key to a circular economy. Keeping a product in a good condition, through maintenance, repair and refurbishment, retains the value and functionality of that product for a longer period; moreover, using a product for longer prevents the generation of waste and postpones the manufacturing of replacement products, thus saving resources, including the energy involved in production. Product design is critical to this.

To increase a product's lifetime, either it can be made more durable by choosing materials such as wood or bioplastics that do not degrade, or it can be designed to be cleaned, maintained, repaired or upgraded

Table 4.1 Estimates of food waste in the EU, 2012

Sector	Total food wastage (million tonnes)	Per capita food wastage (kg per person)
Primary production	9.1 ± 1.5	18 ± 3
Processing	16.9 ± 12.7	33 ± 25
Wholesale and retail	4.6 ± 1.2	9 ± 2
Catering and restaurants	10.5 ± 1.5	21 ± 3
Households	46.5 ± 4.4	92 ± 9
Total food wastage	**87.6 ± 13.7**	**173 ± 27**

Note: Food wastage estimates include food and inedible parts associated with food; 95% confidence intervals.

Source: Vittuari et al. (2016) based on data from the FUSIONS project.

Box 4.5 The donation business model for food waste prevention

From a socio-economic point of view, food waste prevention through charity-related channels can produce a double dividend: food waste reduction and support to the part of the population in greatest need, both of which are high-priority objectives in EU Member States. According to Schneider (2013), the donation of food that is still edible can be seen as a specific application of urban mining, as food is recovered for its original purpose — human sustenance. However, not all food collection and redistribution through food banks and other channels can be considered food waste prevention, given that some of this food is sourced from donations of food that would not otherwise have been wasted.

The food bank channel is gaining pivotal importance in many countries. According to the European Association of Food Banks (FEBA), there are a total of 326 food bank organisations involved in food redistribution in 23 countries in Europe (FEBA, 2017). In 2016, FEBA associates collected and redistributed 531 000 tonnes of food to 6.1 million people in Europe with the help of 37 200 charity organisations. (FEBA, 2017).

Food recovery through not-for-profit and charity organisations can be seen as a win-win solution for reducing food waste while supporting people in the greatest need. Indeed, waste prevention and the environmental dimension of food recovery are increasingly emphasised in the mission statements of food banks in many countries, because this can give additional voice and acceptance to these organisations in the public and policy arenas (Alexander and Smaje, 2008; Schneider, 2013). However, there are very few comprehensive quantitative evaluations of either the environmental or the social benefits.

Food donations can thus serve the dual purpose of preventing food waste and providing social benefits. They are controversial, however, as they tackle the symptoms rather than the root causes of a malfunction in the social security system (Ari Paloviita, Teea Kortetmäki, Antti Puupponen, Tiina Silvasti, 2017).

Box 4.6 Using berry kernels, a processing waste of juice production

In the production of fruit juices, a residue of fruit pulp and kernels is generated. These 'press cakes' are typically used in the production of animal feed or as fuel for bioenergy production. However, the value that can be obtained from these applications is relatively low.

The Belgian company EcoTreasures separates the berry kernels from the press cake of blueberry, cranberry, raspberry and strawberry (Jonckheere, 2014) to produce a range of fruit-seed oils. All these oils are rich in unsaturated fatty acids, antioxidants and vitamins, and can be used in cosmetics or food supplements. In order to fully close the cycle, EcoTreasures also investigated how to fully use the entire berry press cake, not just the kernels. A substrate high in vitamins and minerals can be made by drying the cake, which can then be used as an additive in the baking industry to add a fruity taste and colour to biscuits and pastries. The company's annual production capacity is 4 000 kg for oils and 50-60 tonnes for side products.

easily (Sherwood et al., 2016). When selecting an appropriate lifetime extension strategy, it is important to consider consumer needs and behaviour, as well as the whole system of which the product is a part — manufacturers, users, service providers and recyclers all have a role to play.

4.4.1 Extending the lifetime of bio-based products

Although biomaterials are often recommended for short-lived products, such as packaging, the arguments in favour of lifetime extension are equally valid for bio-based products. Using a bio-based product for longer not only postpones the generation of biowaste but also reduces the need to manufacture replacement products and therefore procure more biomass. The need for manufacturing processes and the need to transport new products are thus eliminated, together with the associated, mainly fossil fuel-based, energy consumption.

Many companies in a wide range of sectors have already pioneered lifetime extension strategies. In the field of furniture, for example, IKEA has been piloting various initiatives across its European stores to see how they can build circularity into their offer to customers (Hullinger, J., 2016). The company aims to support customers to care and repair, rent, share, bring back and resell their IKEA products to prolong product life.

Box 4.7 Fast fashion versus durable fashion

Despite the fact that the environmental impact of manufacturing technologies for textiles and clothing has decreased over the last 25 years, some of the gains have been overtaken by an increase in overall production and consumption volumes. Not only has the relocation of textile industries to Asia made clothes cheaper, the use of lower-quality textiles and the introduction of fast-fashion cycles have deliberately shortened the lifespan of clothes. Although reuse and recycling of clothing has also increased, this only partly offsets the growth in consumption, the proliferation of textile waste and the associated environmental and social impacts.

One way to improve the sustainability of the textile industry is to extend the lifespan of clothing (EC DG ENV, 2012). To achieve this, efforts must be made to increase consumers' attachment to clothing by, for example, designing clothes as semi-finished products that can be personalised using fast digital manufacturing technologies such as textile printers. In this way, a consumer could select and create their own style, colours and look. Furthermore, services that allow customers to rent, lease, share or modify garments could offer new business opportunities and stimulate manufacturers to produce higher-quality garments that will be used for longer, while increasing consumers' willingness to pay more for high-quality clothing that can be adapted to their needs and preferences throughout their lifetime (Niinimäki and Hassi, 2011).

In November 2011, the outdoor clothing brand Patagonia published an advertisement telling consumers 'Don't buy this jacket' to raise awareness of the environmental footprint of clothing and the unsustainability of overconsumption (Patagonia, 2011). Patagonia's Common Threads Initiative wants to encourage consumers not to buy what they do not need, to repair what is broken and to donate clothes they no longer need, and to stimulate separate textile collection and recycling in order to prevent clothes from ending up in landfill or being incinerated. In support of these goals, Patagonia pledges to produce durable, multifunctional clothing that is not prone to fashion trends, while supporting repair and second-hand sales through its Worn Wear website (Patagonia, 2017).

In IKEA's stores in Belgium, shoppers are encouraged to bring back furniture and are given five options: sell, renew, repair, return or donate. Two of the options, sell and repair, are offered for IKEA furniture only, but the other three are available for furniture bought elsewhere. Such schemes are still the exception rather than the rule, and their effect on overall material demand will, to a large extent, depend on consumer behaviour and particularly on possible rebound effects (alternative purchases with the money saved).

In the future, comparable programmes are envisioned to make it easier for customers to access lost or broken parts. The company hopes to install a 3D printer at every location, so that customers can have broken replacement furniture parts made on the spot (Dalheim, 2016). Furniture blueprints will also be made available, so customers with their own 3D printers can make new parts at home. The goal is to educate customers and encourage them to care for their products rather than throw them away. IKEA does not expect the programme to expand in the near future, but believes it could within the coming decade.

Material durability is a particular challenge when using biomaterials in long-life applications. Many biomaterials decompose with time, especially when exposed to certain climatic conditions that favour decay by bacteria, fungi or insects (e.g. high humidity, high temperatures). As a result, varnishes, coatings or chemical-impregnating agents are often used to extend the durability of biomaterials, causing problems at end of life, as many are regarded as contaminants. For instance, treated wood products cannot be composted at end of life, and often cannot be recycled, as they would contaminate pure wood waste streams. As a consequence, treated wood waste is typically incinerated (with or without energy recovery).

The product lifetime of biomaterials, however, can be extended without the addition of technical materials if certain precautionary measures are taken to ensure that the appropriate type of biomaterial is used in a given context. For wood, for example, a classification system has been developed that indicates which types of wood are suited for use in different contexts, for instance in water, soil or a dry environment (VIBE, 2007).

Regardless of the material used, to make lifetime extension technically possible and economically viable, increasing the longevity of products will also require major adaptations to company structures, cultures and core activities, as well as product design and sales models. If successful, lengthened lifetimes will reduce product sales. To maintain company revenues, a shift will be needed from traditional product sales towards the establishment of long-term customer relationships, into which repair and upgrading services are incorporated.

Box 4.8 Cascading the use of wood

Wood cascading in the EU happens in a variety of forms and contexts. It is used for construction, paper and bioenergy production and a significant part of the system is based on circular flows of recovered paper and wood from both industrial processing — for example wood residues from sawmills going to the particle board industry — and post-consumer collection of, for example, waste paper (Mantau, 2012).

From a technical perspective, cascading takes place when wood is processed into a product that is then used more than once, either as a material or to generate energy — burning and incineration of wood is regarded as the final step in the cascade (Vis et al., 2016).

From an environmental point of view, cascading wood — especially when multiple steps are involved — is generally more advantageous than direct energy use, although each individual case requires investigation (Fehrenbach et al., 2017). An economic assessment of wood's material use also shows distinctly better results for cascading in terms of added value and employment (UBA, 2013).

Multiple barriers to cascading wood need to be overcome to realise its full potential. These barriers include technical barriers, such as the cleaning of contaminated waste wood; economic barriers, such as the relatively low price of virgin wood relative to the costs associated with the collection, sorting, cleaning and application of used wood; and governance barriers, such as the lack of integrated approaches to energy and material applications of biomass. In addition, there is no EU-wide obligation for the separation of recyclable wood at the source, although such obligations do exist for glass, plastics, metals and paper.

Measures identified to promote cascading focus largely on the recovery of post-consumer wood — in line with existing circular economy and resource efficiency initiatives (Vis et al., 2016). The effective national implementation of the European waste hierarchy and reliable classification and sorting systems for post-consumer wood are crucial for the establishment of functional recycling systems and multistage cascades (Dammer et al., 2016). Substantial efforts are also needed, however, to address the current imbalance between the material and energy uses of industrial residues that have a significant potential for cascading. The fact that the energy and material uses of biomass are dealt with in different policy domains hampers their integration (Kretschmer, 2012). As long as the bioenergy sector is heavily subsidised, it is unlikely that more effective wood cascades will be established or improved throughout Europe (Dammer et al., 2016).

In addition, fundamental changes in consumer perceptions and behaviour will be needed. Consumer demand for product longevity varies across different product categories: durable, expensive service products such as furniture are most likely to benefit from lifetime extension possibilities, as well as products that trigger a kind of emotional attachment, such as musical instruments (Schifferstein and Zwartkruis-Pelgrim, 2008). For ICT products, such as mobile phones, it is proving more challenging to overcome the consumer's inclination for novelty. Moreover, numerous legal, design and systemic challenges hinder the implementation of circular business models in the mobile phone industry (Watson et al., 2017).

4.4.2 Cascading the use of biomass

Currently, the lifetime extension of biomaterials is mostly mentioned in relation to a cascading use of biomass as a strategy to keep biomass resources in material applications with a high added value for as long as possible, before sending them to energy recovery (Vis et al., 2016). Cascading use of biomass resources improves the sustainability and circularity of the bioeconomy by extending the available biomass resource base, while keeping the embedded carbon sequestered in material applications for a longer time.

The importance of the cascading use principle has already been recognised by several EU institutions; however, there is a strong need for policymakers, researchers and industry to agree on a common concept (Dammer et al., 2016). The most common interpretation of cascading takes time into account as well as the creation or preservation of value — mostly economic added value, but this could be supplemented with indicators of environmental and social value. However, as value optimisation depends on the local context and the quality of biomass, it is not possible to capture all considerations

Box 4.9 Cascading and loop closing for textiles

The textile industry in the EU produces around 12 million tonnes of waste a year, much of which ends up in landfill and a significant percentage (18 %) is incinerated (EASME, 2015).

Closed loop recycling of textiles: relooping fashion initiative

It takes about 8 000 litres of water to produce 1 kg of cotton, which is the average amount of material needed for a pair of jeans (Fletcher, 2014). The cultivation of cotton also requires large quantities of pesticides and chemicals, and energy and fuels are also needed for producing and transporting the textiles around the globe. The recycling of old cotton clothing into new cotton fibre is challenging, as fibres shorten when recycled, which makes them unsuitable for spinning into new thread. Producing recycled cotton fabric therefore always requires the addition of new cotton fibres, making it impossible to achieve 100 % recycled textiles.

The Finnish Relooping Fashion initiative (Relooping Fashion, 2016) and the Trash-2-Cash project (2018) aim to pilot a closed circular system for textiles. Using a chemical recycling process based on cellulose dissolution, post-consumer cotton can be converted into cellulosic fibres, which are even better quality than the original cotton fibres and which can be mixed in a variety of textile formulations. Moreover, the resulting cellulose-based fabric can be recycled again and again, without the need to add harmful chemicals or new fibres. This closed-loop recycling prevents the incineration or landfill of cotton-textile waste and eliminates the need for additional virgin cotton, with its associated environmental impacts. Alongside technical innovation, a new business model has been developed to share the added value across the textile value chain.

Cascading use of textiles: giving textile waste a second life as a construction material

The INPAT (impact noise insulating panel from textile industry waste) project, a project funded by the EC under the CIP-Econ-innovation Programme (INPAT, 2017) developed an innovative application for recycled textile-production waste (flock dust, cut fibres and resins), namely in sound-insulating panels, which also have good thermal properties and are easy to install, for the construction industry. When the panels reach the end of their useful life, they can be remilled and used in similar applications, for example in the car industry.

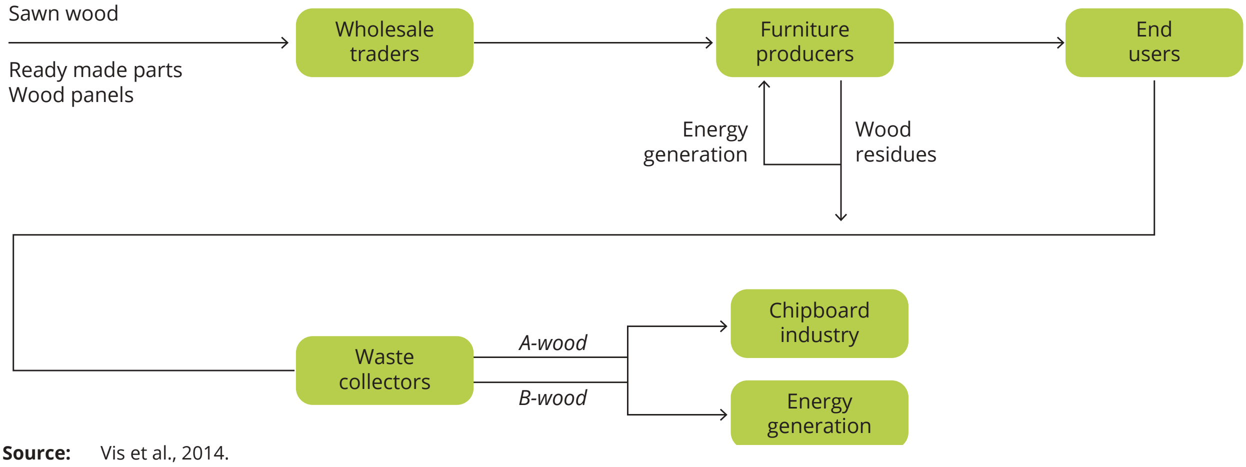
in a fixed preference list or value pyramid. Still, such representations are often used to prioritise applications such as food and pharmaceuticals over energy and fertiliser (Vis et al., 2014).

The potential for cascading is greatest in the wood sector (Box 4.8), although the concept can be broadened to natural fibres, such as cotton, hemp, jute and sisal, as well as bioplastics. Natural fibres used to make textiles can be recovered after use, reused in textiles and later turned into insulating or composite materials. Bioplastics can be manufactured from plants containing starch and sugar such as maize and sugar cane. The production of PLA from maize can be used initially as a textile and then repeatedly as packaging material (Essel, 2014).

When setting up a cascading approach, different markets need to be aligned: the supply of end-of-life waste should be met by a demand for the next application, in both time and space. This poses particular challenges to getting cascades up and running in an economically viable way.

Figure 4.4 shows an example of a current wood cascade. Wood residues and contaminated post-consumer wood (B-wood) are used for energy generation, while uncontaminated post-consumer wood (A-wood) is used as a resource for the production of chipboard panels. Some companies offer furniture in which recycled wood, for example waste scaffolding material, is visibly used in new products (Vis et al., 2014).

Figure 4.4 Wood use in the furniture sector



Source: Vis et al., 2014.

5 Circular bioeconomy: a systems perspective

In both the policy and innovation arenas, the bio- and circular economies are largely viewed as separate, each driven by its own policy, and by research and innovation. The various initiatives are only loosely connected, and more synergy could be created. In this chapter, the case is made for a more integrated and systemic perspective to optimise the use of biomaterials and to create a sustainable circular bioeconomy.

Key points ([7]):

- Circularity can help to reduce competition for land and aquatic resources and thus contribute to the mitigation of climate change and biodiversity loss, but ultimately a coherent perspective on the main policy interventions is necessary.
- A sustainable and circular bioeconomy would keep resources at their highest value for as long as possible through cascading biomass use and recycling, while ensuring that natural capital is preserved. This would have the following implications for governance:
- Policy interventions should be geared towards the reduction of environmental pressures along the entire value chain.
- Bio-based approaches should be tailored to the specific use context in order to maximise the benefits of bio-based and biodegradable products.
- Technological innovation should be embedded in wider system innovation that also tackles consumer behaviour, product use and waste management.

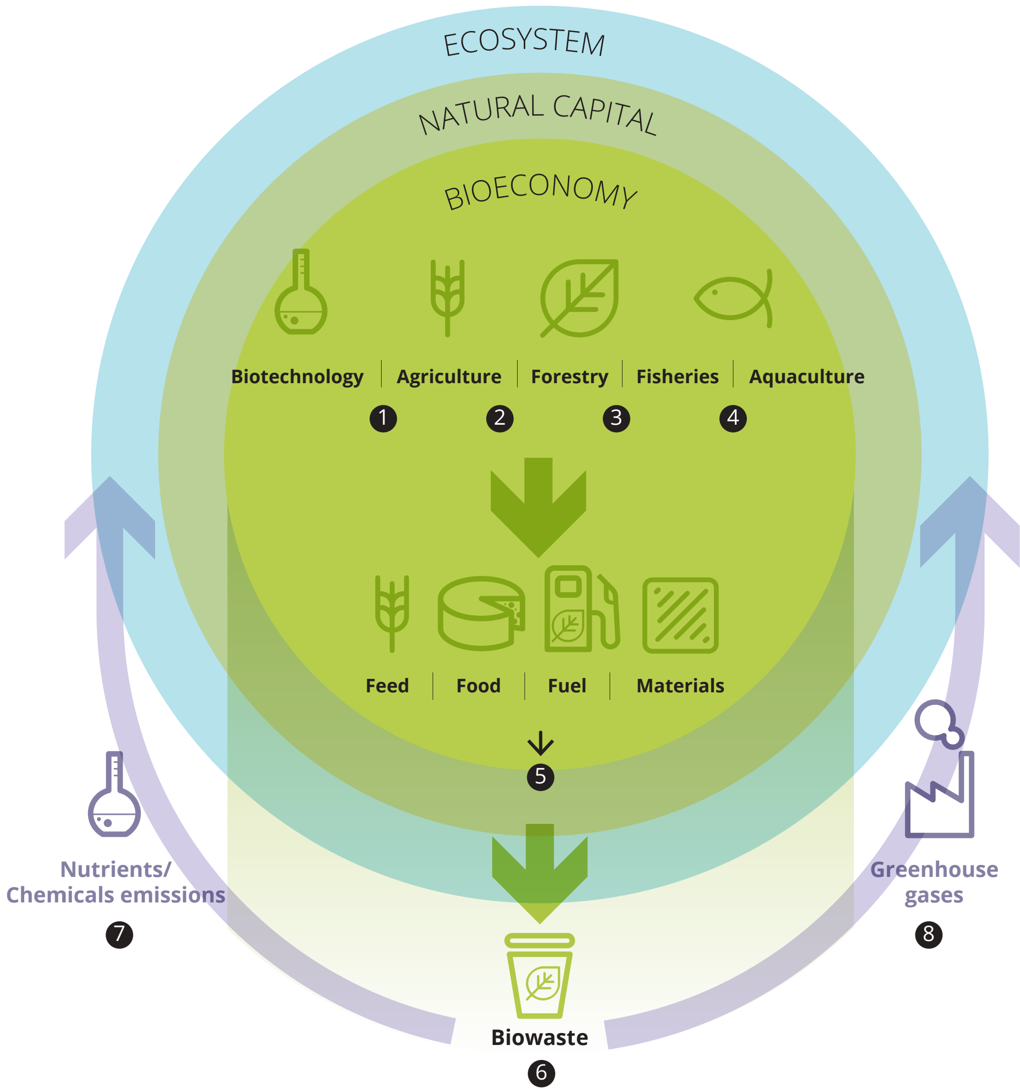
5.1 Balancing sustainability goals

Resource needs in an expanding bioeconomy are likely to increase. There are many tensions and trade-offs between the various approaches, as well as possible rebound effects. The pathways and good practices outlined in the previous chapters are summarised in Figure 5.1. The transition to renewable energy systems in Europe, for example, relies in part on biomass. Farmland expansion and/or intensification could cater for this increasing demand, but probably at the expense of biodiversity and ecosystem resilience. Unintended rebound effects may, for example, result from the valorisation of food waste, which conflicts with the aim of preventing food waste in the first place.

Essential in this respect is the coherence of overarching policy agendas (circularity, the bioeconomy, decarbonisation) and the major sectoral policies (waste, energy, transport, agriculture) that could deliver tangible results. Integrating environmental concerns into sectoral policies has received more and more attention over the years, but the coordination between different policy agendas, including the cross-checking of goals and instruments, could further improve. The EU common agricultural policy, for example, has seen several reforms with an increasing focus on environmental aspects. However, it still lacks an overarching intervention logic regarding resource efficiency in terms of land use, energy and material inputs (fertilisers and pesticides), and the generation of residues

([7]) See body text for references.

Figure 5.1 Pathways and good practices for fostering a circular bioeconomy



Pathways

1. Replacing fossil-based products
2. Expansion of farmland
3. Intensifying biomass production
4. Aquatic biomass sourcing
5. Changing consumer behaviour
6. Separating biological and technical material cycles
7. Improving nutrient balance
8. Improving energy balance

(Greening Europe's agriculture, in press) (EEA, 2017b). Opportunities to minimise biodiversity loss, increase circular nutrient use and decrease greenhouse gas emissions may thus be missed.

A more integrated policy approach to our food, energy and transport systems would be needed to effectively reduce environmental pressures along the entire value chain of materials, products and services. This implies coherent measures aimed at producers as well as consumers, with legislation, subsidies, green procurement, taxation and product labelling as important policy tools. Life-cycle assessment can inform such approaches and the related public debate on their trade-offs.

5.2 Combining technical and social innovation

Several concrete areas for improvement of the environmental potential of bio-based and biodegradable materials can be identified. Although they replace fossil or mineral resources, their treatment is often not truly circular on account of being mixed with non-biodegradable materials, and because of inadequate disposal and waste management systems. Consumer behaviour, technical and logistical innovations and new business models should go hand in hand to optimise environmental performance. For example, using biomaterials in car components (Box 4.1) is only a partial solution, as the plastic components will not (and should not) return to the biocycle. Similarly, the use of biodegradable plastic in pens will contribute little to circular material use if such plastic cannot be separated from other components, such as ink and metal writing heads, that are not biodegradable.

The same goes for shoes made from pineapple fibres (Box 4.3). While this is a good way to use crop residues on the local scale, the application of finishing products and colourants has to be considered with care: if the shoes and other products made from the pineapple textile are meant to be part of the biological cycle, then the dyes and lacquers used in their manufacture should be compostable as well.

Many bioplastics are difficult to sort and separate from conventional plastics. A lack of consumer awareness of the differences between conventional and bio-based plastics hampers the recycling process (Giljum et al., 2016). For instance, although PET and PLA have similar appearances, their chemical composition is different and they behave differently during the recycling process. Mixing even small quantities of these polymers could disturb the mechanical recycling process.

The use of compostable materials in products poses similar challenges. Often, these products contain a mixture of compostable and other materials, hampering recycling and making it impossible to send them to a composting installation. Even fully compostable products often end up not being composted because of inadequate collection systems. Compostable plastic carrier bags, for example, are often not allowed to be put in a biowaste bin as a measure to prevent the disposal of non-compostable plastic bags. In any case, industrial composting installations with mechanical sorting would most likely remove such compostable bags from the biowaste stream, together with other plastics bags made from fossil fuels.

Such incompatibility between new materials and existing collection and sorting systems needs to be tackled by aligning material innovation with infrastructure innovation and renewal, and with sorting policies informing consumers. Box 5.1 provides two examples of technological innovation

Box 5.1 Biodegradation and recycling

A comprehensive approach to compostable bags helps Milan to increase food waste recycling

Households in Milan were issued with a vented bin with compostable plastic bags for food waste as part of a project to increase food waste collection (WEF et al., 2016). At the same time, single-use non-compostable plastic bags were banned from supermarkets and replaced with compostable ones, to prevent the problem of having to filter out all plastic bags from biowaste. The result of this concerted introduction of compostable plastic bags for all uses decreased the content of non-compostable materials in collected food waste, while its collection rate tripled from 28 to 95 kg per person. As a result, the food waste could be used as input by an industrial composting facility to produce compost good enough for use by farmers, contributing to the replenishment of soil nutrients.

PEF: a bio-based, recyclable alternative to PET

Avantium, a Dutch technology company, developed polyethylene furanoate (PEF), a biopolymer made from plant-based sugars that has better barrier and thermal properties than fossil-based PET, and which, as such, is an interesting alternative to PET packaging for beverage bottles for example. In addition to the technical innovation itself, Avantium has demonstrated that PEF can be effectively recycled and that it does not hamper the recycling of PET, as mixing PEF in the PET recycling stream does not affect the mechanical or physical properties of PET. Avantium is working with brand owners and the recycling industry to integrate PEF in the recycling of PET in the short term and to establish a dedicated PEF to PEF recycling infrastructure in the longer term, once PEF-based products are used in larger volumes (Avantium, 2017; BBI Europe, 2017).

Source: Giljum et al., 2016.

being embedded in infrastructure development and behavioural change.

5.3 Upscaling and anticipating side-effects

The upscaling of innovations aimed at improving sustainability can lead to unintended side-effects. Technological innovation starts in the confined environment of a laboratory, where elements such as supply limitations, logistics and economies of scale do not apply. These elements, however, will define the sustainability of the innovation when it is implemented on a large scale. How much pressure will a switch to a fully bio-based chemical sector put on land resources, for example, and will this lead to competition with food production? Furthermore, can a continuous supply of biomaterials of sufficient quality be guaranteed?

Fossil resources are particularly suited to large-scale and centralised production models, as there is a year-round steady supply and they are of relatively constant quality. Biomass resources, on the other hand, have a seasonal and distributed supply base, are prone to decay and are very heterogeneous in composition and quality. This requires well-connected and interdependent networks and sufficiently flexible operation models to respond to changes in feedstock availability and product demand. Biorefinery concepts can offer this flexibility.

It is important to consider downstream implementation aspects as early in the innovation process as possible. Fleece sweaters, for example, have long been promoted as an effective way of recycling waste PET polymers into high-quality clothing, but Hartline et al. (2016) found that when such synthetic garments are washed, microfibres are released in the washing water and ultimately end up in rivers, lakes and eventually oceans, contributing to marine 'plastic soup' pollution. This problem remains largely unsolved.

Microbeads in cosmetics provide an example of how certain measures at the early design stage can help to mitigate negative side-effects. Microbeads, plastic particles of less than 0.5 mm in their largest dimension and made of PE or PP, are commonly used in (among other things) personal care products such as toothpaste, sunscreen and cosmetics. Their small size allows them to pass through waste water filter systems and end up in oceans. A research team from the Centre for Sustainable Chemical Technologies (CSCT) at the University of Bath, United Kingdom, has developed microbeads made from cellulose fibres. These beads, which can be made out of waste products from the paper industry, have the same properties as plastic microbeads, but biodegrade soon after use (Knack, 2017).

5.4 System-design principles

In summary, the following principles can be applied to governance and innovation for a circular bioeconomy:

1. Policy interventions should be geared towards the reduction of environmental pressures along the entire value chain. This requires explicit sustainability targets, recognition of trade-offs and coherent measures aimed at producers as well as consumers.

2. Bio-based approaches should be tailored to the relevant use context. More specifically:

   - Wherever possible, innovation that diminishes material and energy use and keeps products and materials in circulation should be prioritised. This helps to decrease pressure on biomass production and prevents the unwanted dissipation of technical materials to the environment.

   - Use bio-based, non-biodegradable materials only where they can be effectively recycled at end of life.

   - Bio-based, biodegradable materials should be used where the risk of dispersion into the ecosystem is high, such as lubricants, materials subject to wear and tear, and disposable products.

3. Technological innovation should be embedded in wider system innovation that also tackles consumer behaviour, product use and waste management. This will greatly enhance the success of sustainable innovation and will help to anticipate scaling problems and unintended consequences. Questions such as 'what will be the impact on the local and/or global biocycle of this bio-based innovation when it is applied in this context, and when will it be applied at scale?' should be asked. Life-cycle thinking, when properly applied, can be of great help in tackling such questions.

Innovative companies can use these principles to guide the evaluation and steering of the sustainability of a specific innovation in the bioeconomy. In the case of Carlsberg's Green Fiber Bottle (Carlsberg, 2017), for example, the material design is compatible with a circular bioeconomy because it is both recyclable and biodegradable, while the wood is sourced from sustainable sources. The recyclability enables the recycling of the bottles through a return system, while their biodegradability acts as a failsafe if bottles end up in the environment. Carlsberg is also carrying out marketing to raise awareness among consumers of changing their consumption behaviour. However, the second design principle also requires Carlsberg to carefully consider the potential impacts of upscaling their product innovation to the global market. Would there be a sufficient supply of sustainably sourced wood if the Green Fiber Bottle were to be produced at the full scale?

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