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ETC Report: Are we losing resources when managing Europe´s waste?

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Authors:
Margareta Wahlström (VTT), Elina Pohjalainen (VTT), Tuuli Teittinen (VTT),
Ann Van der Linden (VITO), Maarten Christis (VITO), Saskia Manshoven (VITO)

ETC/WMGE consortium partners: Flemish Institute for Technological Research (VITO), CENIA, Collaborating Centre on Sustainable Consumption and Production (CSCP), Research Institute on Sustainable Economic Growth of National Research Council (IRCrES), The Public Waste Agency of Flanders (OVAM), Sustainability, Environmental Economics and Dynamic Studies (SEEDS), VTT Technical Research Centre of Finland, Banson Communications Ireland (BCI), The Wuppertal Institute for Climate, Environment, Energy (WI), Slovak Environment Agency (SEA)

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European Topic Centre on Waste and Materials
in a Green Economy
Boeretang 200
BE-2400 Mol
Tel.: +14 33 59 83
Web: wmge.eionet.europa.eu
Email: etcwmge@vito.be

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The authors of the report are: Elina Pohjalainen (VTT), Tuuli Teittinen (VTT), Ann Van der Linden (VITO), Maarten Christis (VITO), Saskia Manshoven (VITO) and Margareta Wahlström (VTT).

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Executive summary

Significant amounts of valuable resources can be lost due to sub-optimal waste management, for example through landfilling, incineration, down-cycling or non-targeted recycling. In this report, a number of waste streams have been considered and analysed: end of life batteries, waste electrical and electronic equipment (WEEE), plastics waste, textile waste and rubber waste. The material losses associated with these waste streams have then been considered and, to the extent possible, quantified. The waste streams have been chosen based on the following overarching criteria: content of valuable materials, policy relevance, environmental sustainability aspects and mass or value.

Key information collected for each waste stream include general description of the stream, identification of their policy relevance, material flows and current waste management options. For each waste stream, the types of losses are assessed and the reasons behind these losses are analysed. A special target of the work is to assess the loss of critical raw materials.

End of life batteries. Over 1.9 million tonnes of waste batteries are generated in the EU every year (Eurostat). Major part of the batteries (in terms of both batteries placed on the market and collected as waste) are lead-acid batteries from automotive and industrial applications. Collection and recycling rates of waste batteries strongly depend on the battery type. For example, the recycling of lead-acid batteries is a well-established scheme and it is estimated that 99 per cent of lead-acid batteries are collected for recycling at end-of-life and that only a small amount is unavailable for recycling due to net export of end-of-life vehicles. Average collection rates for portable batteries are much lower (46 per cent in the EU28 in 2017) and a significant amount is thus estimated to end up in municipal waste. In particular, batteries embedded in electronic appliances often do not reach official collection but are either stocked at consumers' homes, exported outside EU in used electrical and electronic equipment (EEE) or end up in WEEE recycling. Different batteries contain a wide variety of materials such as base metals, critical raw materials (e.g. antimony in lead-acid batteries, rare earth elements in nickel-metal-hydride (NiMH) batteries and cobalt and natural graphite in lithium ion batteries) and hazardous substances. The recovery of materials from the waste batteries is driven by waste policies and economic value of the materials.

WEEE. The amount of WEEE generated in Europe is over 10 million tonnes per year, of which currently roughly 40 per cent is officially collected for recycling. A significant amount of WEEE is in stock at people's homes and does not end up in official collection. Part of WEEE is also thrown in the waste bin, recycled under non-compliant conditions, scavenged for valuable parts or exported outside Europe. Improvements in WEEE collection systems as well as awareness rising are needed in order to increase the rate of officially collected WEEE. WEEE include various metals and critical raw materials. Even though base metals such as ferrous metals, aluminium and copper from WEEE are already recycled to a large extent, not all metals can be effectively recovered. The recovery of most critical metals has not yet been commercially established and therefore they are mostly lost within the recycling process. Also, design issues that increase marketability and durability of high-tech EEE products create recycling challenges for separation of the components and materials recovery. For example, miniaturization and structurally integrated materials make disassembly and recovery more difficult.

Plastic waste. The dominant use of plastics is in packaging. The plastic packaging waste generated in 2016 in Europe reached 16.3 million tonnes, of which 43 per cent (7 million tonnes) was recycled and 57 per cent or more (9 million tonnes) disposed in landfills or incinerated with energy recovery (Eurostat). A characteristic of the packaging products is, that after a short use time, it ends up as waste. Especially the single-use plastic packaging is creating concern. Plastic waste is rarely recycled in the same plastic products, because plastics recyclables seldom meet the material requirements for the application. The exception to this are PET bottles of which 57% is collected for recycling in Europe. However, the recycled content of PET in recycled bottles accounts on average for only 11 per cent.

The second largest application area for plastics is in the construction sector. The generated amount of plastic waste from construction was reported as 1 million tonnes in 2016 (Eurostat). In the construction sector, the plastic products remain in buildings for decades before they are removed and often appear in paints, glues and binding agents. Construction products consist of several materials often attached through gluing, making the separation of materials for recycling difficult. A specific challenge is also the identification of the plastic material polymers in the building. Only a few plastic products (for example PVC windows or tubes) are identified as suitable for recycling. Of plastics materials, PVC has the highest recycling rate of 32 per cent.

The share of plastics in the automotive sector has been increased in the last decades to nearly 20 per cent of the weight of the vehicle. In the automotive sector, the focus on recycling is typically on metal recycling. During the dismantling process, some plastic products, like bumpers, can be removed and potentially reused or sent to recycling. However, often, brand specification, material degradation and challenges to dismantle bumpers without damage (due to attached wires) lead to the situation where bumpers are typically recycled in other applications with lower requirements to the material (downcycling). Most of the plastic fraction ends up in the shredder waste fraction which is incinerated or landfilled.

In recycling of WEEE, focus is on the valuable metal recovery. Plastics from WEEE are not recycled at a high rate, only some plastics easily separable from products are mechanically recycled to new raw materials. A condition for recycling is that the plastic does not contain flame retardants. Small devices are often lost because they are not brought to collection but instead stored at home or sometimes misplaced with household waste due to their small size and light weight.

In summary, it has been estimated that less than 5 million tonnes of the plastic waste are actually recycled, because part of this stream is misplaced in household waste or lost in processing. Plastic waste is typically only recycled a few times due to material degradation and typically downcycled. Only 6 per cent of new plastics materials are derived from recycled plastics.

Textile waste. The consumption of textiles is estimated at 9.55 million tonnes (Europe, 2007). The yearly discard is estimated to be 5.8 million tonnes, of which around 20% is currently collected for reuse or recycling. Of these separately collected textiles, the reusable fractions are mainly exported and sold in foreign markets, while the non-reusable fraction is downcycled. This makes the amount of textiles that are not recovered significant. Therefore, the potential environmental gain that could be achieved by reusing or recycling is high. The environmental impact, in terms of greenhouse gas emissions (expressed in CO_2-eq), related to the production of textiles is about 18.3 kg per kg of textiles. The reuse of textiles can thus avoid significant amounts of greenhouse gasses. Also the recycling of textiles will avoid environmental impacts, though the possible gains are much lower compared to those of reuse. Because Europe is a net importer of textiles, the avoided impacts will mainly be outside of Europe.

Rubber waste. Natural rubber is a biotic material that is listed by the European Commission as a critical raw material (CRM). Natural rubber is mainly used in the production of tyres, which are responsible for about 75 per cent of total EU rubber consumption. Waste generated from end-of life tyres in EU was 3.36 million tonnes in 2016, of which 46 per cent was recovered for recycling (Eurostat). The recycling of tyres is an example of open-loop recycling. For example, end-of-life tyres are shredded into rubber granules that can be used in various applications. Mostly, natural rubber is recovered together with other materials and the closed-loop recycling of natural rubber back to the original application is not possible.

Key findings

The reasons for material losses are typically waste-specific and cross-linked, for example waste quality (heterogeneity) and the lack of cost-efficient technologies.

The key findings on the causes for resource losses are the following:

- loss in collection (common for many streams):
    - lack of awareness, misplaced with household waste;
    - wastes are scattered both geographically and across stakeholders (e.g. consumers and businesses);
    - huge differences in recycling rate across Member States;
    - export outside Europe.
- poor material quality for new products:
    - waste from complex products where different material parts cannot be separated (liberated) into different fractions for further processing;
    - materials heterogeneity, mixing of several waste streams, contamination from use;
    - lack of sorting technology (plastics polymers with same physical properties, textile);
    - content of hazardous substances.
- technology challenges:
    - cost-efficient technology: low price of virgin materials compared to processing costs;
    - material complexity (due to design, different materials are not easily separable for recycling, additives hampering recycling).
- lack of market or demand for recyclables:
    - low prices for virgin materials;
    - lack of recyclers operating due to lack of stability in the supply of recycled materials and related low market demand for recycled materials;
    - lack of trust on quality (lack of standards).

In conclusion, the waste streams in focus in this report are often downcycled and rarely recycled into the same application. Achieving real product reuse or high-quality recycling and closed loops, will require improvements in the collection infrastructure, increased consumer awareness and design of products for reuse or recycling from the start. This will also require an improvement in communication among stakeholders in the value chain (product designers, recyclers, end-users of recovered materials).

1 Introduction

1.1 Background

In the current material management system, many resources are lost for the economy, for example because the material ends up in landfills, incinerators, or because it is downcycled or not targeted during the recycling process.

In 2017, the ETC/WMGE and EEA explored options for doing analyses on where and how resources are lost due to a number of reasons, such as non-recyclability of products, improper collection, sub-optimal management of waste, lack of recycling technologies, competition of recycled materials with virgin materials and presence of hazardous substances together with valuable materials. This resulted in a scoping paper on lost resources, with the aim to generate some background information for future EEA products, including the SOER 2020.

The aim of this working paper is to review and update the previous work done in the 2017 scoping paper. On this basis, the EEA and the ETC/WMGE will draft a short EEA briefing on the loss of resources, providing well-supported messages. The briefing will be published on the EEA website.

The lost resources topic, which is linking waste and resources, is highly relevant in the context of Circular Economy. The topic also has links to the following ongoing ETC activities related to Circular Economy or Resource Efficiency:

- task 2.2.1.2 Safe-and-circular-by-design products, with focus on chemicals and plastics;
- task 2.1.3.2 Plastics trade and the environment;
- task 2.1.3.1 Mapping of initiatives on plastics;
- task 1.9.1.6 Construction and demolition waste - stay of play;
- task 2.1.2.2: Electronic products and obsolescence; and
- task 2.1.2.1 Textile products and the environment

1.2 Methodology

Based upon the available information and relevance for the EU, five illustrative examples were chosen taking into account the different types of 'losses' throughout the value chain. This also includes the assessment of the loss of critical raw materials. For each type of loss, the reasons behind it will be analysed. The focus of the report is at the EU level, not at country level.

The work started by collecting information on the following candidate streams: mineral waste from construction, metal waste from construction, plastic waste, electronics, neodymium in permanent magnets, batteries, lithium-ion batteries, biowaste, natural rubber and textile waste. These candidate streams were assessed based on the following criteria:

- Policy relevance: the importance of the waste stream from an EU policy perspective. Links to EU circular economy objectives and recycling targets to several of the waste streams.
- Content of valuable materials, especially critical raw materials (CRMs). The European Commission publishes every third year (next list expected for 2020) a list of raw materials, so called critical raw materials (CRMs) that are important to the European economy but at the same time associated with supply risks. This list includes, for example, platinum group metals, rare earth metals, gallium, indium, niobium and cobalt.

- Environmental sustainability aspects (e.g. greenhouse gas emissions from the production of material, resource savings from recycling, leakage of microplastics, water consumption in production)
- Mass or volume of flow, generated in huge amounts (e.g. over 1 million tonnes per year in Europe)

Based on these criteria, five steams were selected for further examination: batteries, waste electrical and electronic equipment (WEEE), plastics waste, textile waste and natural rubber (Table 1.1). Based on data sources such as the JRC Raw Material Information System (RMIS)[1], Eurostat, EU projects, EU studies and relevant scientific articles, the following key information was collected for each selected stream:

- general description of the flow;
- justification for selection of the flow;
- identification of policy drivers;
- masses, mass-flows;
- content of valuable material fractions;
- current management options at end-of-life;
- types of resource losses;
- causes/drivers for losses;
- uncertainties or challenges in data mapping.

[1] Rmis.jrc.ec.europa.eu

Table 1.1: Basis for selection of streams for further analysis. Grey cells indicate significant relevance.

	Policy relevance	Content of valuable raw materials	Environmental sustainability aspects	Mass of the flow
Batteries	Economic importance in future. EU recycling targets.	Contains several CRMs, e.g. antimony, rare earth elements, cobalt and natural graphite.	Linked to new forms of energy supply. Higher recycling rate of certain CRMs from batteries could reduce the supply risk of these CRMs.	Over 1.9 million tonnes of waste batteries generated annually in Europe and the amount is expected to increase in future
WEEE	Fast growing waste stream, contains precious metals and critical raw materials. EU recycling targets.	Contains precious metals and several CRMs, e.g. gold, silver, antimony, beryllium, cobalt, neodymium and indium.	WEEE contain a complex mixture of materials, including diverse substances that pose environmental and health risks if not treated adequately. Higher recycling rate of certain CRMs from WEEE could reduce the supply risk of these CRMs.	Over 10 million tonnes of WEEE is generated per year. WEEE generation is expected to increase in the future.
Plastics	Priority sector in CE; EU Plastic strategy, targets for packaging wastes. Recycling of plastics also relevant for achieving recycling targets for end-of-life vehicles, wastes from electronics and electronical equipment and to some extent also construction and demolition waste.	No CRMs in plastics (some flows might contain antimony, but not of widen interest).	The basic feedstock of plastics is oil. Recycling of plastics can reduce the use of fossil resources and greenhouse gas emissions. Littering problems are also highly of concern.	Over 17 million tonnes of plastic waste generated in Europe annually. Packaging plastics are the biggest sub-stream.
Textile	Targets in Circular Economy Package.	Textiles do not contain CRMs.	The production of textiles causes negative environmental impacts such as significant CO_2 emissions, high water use and chemical pollution.	Over five million tonnes of textiles are discarded every year in Europe.
Natural rubber	EU consumption of natural rubber is fully dependent on imports, natural rubber is listed as a CRM.	Natural rubber is listed as a CRM.	As a biotic material, several environmental concerns (e.g. disasters, diseases) affect the production of natural rubber. The cultivation of natural rubber itself may cause negative environmental impacts, such as loss of biodiversity.	Tyre industry uses 75 % of EU natural rubber consumption. Waste generated from end-of life tyres is more than 3 million tonnes per year.

2 Batteries

2.1 Overview

Currently, lead acid batteries make up for the major part of the battery market in terms of weight (89 per cent of total mass of batteries placed on the market in EU28 + Norway and Switzerland in 2015) whereas primary alkaline batteries dominate the market in terms of number of battery cells (81 per cent of battery cells placed on the market in EU28 + Norway and Switzerland in 2015)[2] . In the near future, the highest growth rates and major part of the investments are expected in the lithium ion battery sector, especially for the industrial batteries (C. Pillot, 2017). To date, the share of electric vehicles (including battery electric vehicles, BEV, and plug-in hybrid electric vehicles, PHEV) in the total car sales represents only 1.5 per cent in the EU28 in 2017 (EEA, 2018), but the share of EVs is expected to increase in the near future.

In the Directive 2006/66/EC on batteries and accumulators and waste batteries and accumulators (EU, 2006), a division into the following subcategories is made: portable, industrial, and automotive batteries. The overall objective of the Batteries directive is to minimise the negative effects of batteries on the environment (Stahl et al., 2018). Specific targets are set for the collection rate of portable batteries and recycling efficiencies of different battery types. Minimum collection rate set for portable batteries and accumulators is 45 per cent since 2016. Minimum recycling efficiencies set for recycling processes are 65 per cent by average weight of lead-acid batteries, 75 per cent by average weight of nickel-cadmium batteries and 50 per cent by average weight of other waste batteries. An evaluation of the battery directive was published recently by the Commission (EC, 2019), and although it was concluded that the Directive had resulted in many positive outcomes such as reduced use of hazardous substances, there are also deficiencies regarding e.g. the collection of waste batteries and the efficient recovery of materials. Thus, further targets for collection and recycling should be considered in order to achieve the Directive’s environmental protection objectives.

1.92 million tonnes of waste batteries were generated in the EU in 2016 (Eurostat 2016). Collection and recycling rates of waste batteries strongly depend on the battery technology or type. The highest collection rates are achieved for lead-acid batteries, and the lowest for lithium-ion and NiMH batteries (Mathieux et al., 2017). In the ProSUM project, the following mass flows for batteries are estimated:

- all batteries placed on the market: 2.4 million tonnes;
- stock 9 million tonnes;
- waste generated 2 million tonnes in EU28+2 in 2015 (Huisman et al., 2017).

In general, data availability for the collection rates is best for portable batteries. The data availability for automotive and especially for industrial batteries is worse as there are no collection targets set and no reporting obligations exist (Stahl et al., 2018).

Recycling of lead-acid batteries is usually profitable, whereas recycling of other battery chemistries often is not (Stahl et al., 2018). This is due to the differences in chemical composition and construction of different battery types. For example, in lead-acid batteries, around 60 per cent of the battery mass is lead, which can be easily separated from other components after disassembling the battery. In lithium-ion batteries (LIBs), however, a wide variety of materials is used and the active materials are coated as thin layers on the current collector foils which makes the recycling process more complicated (Huang et al., 2018).

[2] Source: database at Urban Mine Platform http://www.urbanmineplatform.eu/homepage

Details of the most important streams are listed in Table 2.1. Most important sub streams are further discussed in section 2.2, with an emphasis on LIBs.

Table 2.1 Most important battery waste streams

Stream	Placed on the market 2015(Stahl et al., 2018)	Current management	Other remarks
All batteries	1.8 Mt (2015) (Stahl et al., 2018) 2.4 Mt (Huisman et al., 2017)	1.92 million tonnes of waste batteries were generated in the EU in 2016. 1.56 million tonnes waste batteries were reported as collected for treatment of which 1.52 million tonnes recycled and 40 kilotonnes landfilled (Eurostat 2016).	Huge variation between battery types in collection and recycling rates, and profitability of recycling.
Sub streams			
Automotive (SLI Lead-acid)	1.1 Mt	Collection rates very high; 99 % of lead-acid batteries estimated to be collected in the end of life, and recycling efficiency of Pb content is over 95 % in most reported EU countries (Eurostat 2017).	Potential loss: export of used vehicles.
Industrial	0.49 Mt		
Lead-acid (industrial)	0.44 Mt	see automotive	
Li-ion (Industrial)	38 kt	Data on recycling of industrial batteries is very limited due to rather long lifetime of these batteries and the fact that they have been on the market for only 5-10 years. Thus, very small battery volumes have reached their end-of-life.	Market of EV/PHEV/HEV is forecasted to increase strongly resulting in growing waste stream in the near future.
Portable	212 kt	Collection target for portable batteries is 45 % and achieved collection rate varies between 30-61 % (Eurostat 2017).	It is estimated that large amounts of portable batteries end up in municipal waste (35 kt annually).
Alkaline (portable)	130 kt	see portable batteries	Some alkaline batteries contain indium, which is listed as CRM.
Li-ion (portable)	37 kt	Collection rates for rechargeable Li-ion batteries are low; typical estimates around 10 % (but high variation between reporting countries, and high uncertainty in the reported values). (Database at Urban Mine Platform)	Industrial recycling processes are focused on recovering Co, Ni and Cu. Li and graphite are usually not recovered.
NiMH (portable)	13 kt	Relatively low collection rates: estimates at Urban mine platform typically between 10-30 % (but high variation among reporting countries, and high uncertainty in the reported values). (Database at Urban Mine Platform)	Market share decreasing due to increase in the Li-ion battery sector. Contain several rare earth elements (REE). REE not recovered in the recycling (Sommer et al., 2015).

More efficient recycling of batteries could contribute to the sustainable use of resources. Currently, various critical raw materials are used in different battery technologies as listed in Table 2.2.

Table 2.2 Critical raw materials used in different battery types. (EC, 2017)

Battery type	Critical raw material	Share of batteries from global use (weight-%)
Lead-acid	Antimony	32
Alkaline	Indium	5
Lithium-ion	Cobalt	42
Lithium-ion	Natural graphite	8
NiMH	Rare earth elements:	
	Yttrium	7
	Cerium	6
	Neodymium	13
	Lanthanum	10
	Praseodymium	12

In the case of lithium ion batteries, cobalt and natural graphite are widely used in the cathode and anode and both are classified as critical raw materials. Mining of Co is highly concentrated: 64 per cent of the global mine production happens in the Democratic Republic of Congo (five-year average 2010-2014) (EC, 2017). Global cobalt demand is estimated to have a growth rate between 7 per cent and 13 per cent in the period from 2017 to 2030 (depending on the growth of electric vehicle market and other cobalt uses). This can lead to a cobalt demand exceeding the supply already by 2020 (Alves Diaz et al., 2018). Natural graphite is also listed as a critical raw material and China is leading supplier with 69 per cent of global production (five-year average 2010-2014) (EC, 2017). However, natural graphite is different from other CRMs used in batteries, as graphite can also be produced synthetically (although this process is highly energy consuming).

2.2 Selected sub streams

2.2.1 Lead-acid batteries

Collection rates for lead acid batteries are very high: it is estimated that 99 per cent of automotive lead-acid batteries are collected and recycled in the EU (study 2010-2012) (Eurobat, 2014). Only a minor amount, about 21,000 tonnes of automotive lead-acid batteries, are unavailable for collection due to a net export of used and end-of-life vehicles (Stahl et al., 2018). Recycling of lead acid batteries is well established and due to the relative simplicity of the process, it is also profitable. Recycling efficiency of Pb content of the lead acid batteries is over 95 per cent in most reported EU countries. Antimony, which is listed as a critical raw material, is used as an additive in lead electrodes of lead-acid batteries. However the use of antimony in lead electrodes has decreased in recent years as the antimony content has declined due to new additives being used (Mathieux et al., 2017). Almost all antimony in lead electrodes is currently being recycled (Dupont et al., 2016) which is the main source for secondary antimony.

2.2.2 Portable batteries

The collection target for portable batteries in Directive 2006/66/EC is set at 45 per cent (EU, 2006). The achieved collection rates vary between 30 and 61 per cent in different EU countries (Eurostat 2017). The collection rates of waste batteries in the EU have increased continuously since 2009, however, substantial amounts of end-of-life batteries are still unreported. Potential explanations for these losses are (Stahl et al., 2018):

- Batteries being disposed of in municipal waste: in the EU28 approximately 35 000 tonnes estimated annually;
- End-of-life batteries stocked at homes by consumers;
- Losses through WEEE (batteries are not removed from appliances and end up in e.g. metal recycling together with WEEE);

- Export (outside the EU) of used EEE with their batteries embedded.

2.2.3 Lithium-ion batteries

Collection rates for portable LIBs are estimated to be much lower than for portable batteries in general: Eucobat estimates around 10 per cent of portable lithium-ion batteries are collected in 2016 (Eucobat 2017). Especially LIBs embedded in appliances are often not removable by consumers and thus end up in WEEE recycling or other unknown whereabouts. In the ProSUM project, material stocks and flows of batteries are estimated. Regarding the battery waste stream (including all battery types), 2,700 tonnes of cobalt waste is generated annually and only 300 tonnes of the cobalt is estimated to be in reported collected batteries compared with 2300 tonnes of cobalt in the unknown and other whereabouts (Huisman et al., 2017).

Li-ion cells and modules are currently recycled in existing industrial facilities using a combination of different operations such as mechanical, pyrometallurgical and hydrometallurgical treatments. In the EU there are around 10 industrial recycling facilities for LIBs with a total processing capacity of 38,000 tonnes per year (Alves Diaz et al., 2018). The current industrial processes utilizing pyrometallurgy are focused on recovering metals like cobalt, nickel and copper. Graphite and lithium are usually not recovered but lithium ends up in slag after the pyrometallurgical treatment. However, when using hydrometallurgical recycling, lithium can also be recovered. To date it has not been considered economically feasible, though. Recycling efficiencies for LIBs and their materials are estimated to be about 95 per cent for Co and Ni, 80 per cent for Cu and 50 per cent for Al, depending on the specific process. The battery management system also contains valuable materials (such as tin, silver, and gold) relevant for recycling (Stahl et al., 2018).

The chemical composition and design of a battery depend on the manufacturer, which causes challenges for recycling as different chemistries (LCO, NMC, LFP etc) of lithium ion batteries are currently not indicated on the battery packs. International standards for battery markings including the chemistry would reduce economic and material losses as well as ensure safe handling of batteries during the recycling process (Tecchio et al., 2018). In the case of EV lithium ion battery packs, the housing of the battery pack and modules corresponds to almost half of the total mass of the battery system and the amount of Co can be as low as 3 to 5 per cent of the total mass. In the directive on waste batteries, the minimum recycling efficiency that must be achieved is set by average weight, and for other battery categories the required efficiency is 50 per cent. Thus the Directive does not promote the recycling of materials that are critical or have a high environmental burden. Instead, it favours recovery of metals that are widely used and abundant in nature (Ellingsen & Hung, 2018).

The worldwide LIB market is expected to grow from 78 GWh in 2016 to 210 GWh at a compound annual growth rate (CAGR) of plus 13 per cent during 2016-2025, and the highest growth is expected in electric vehicles and industrial applications (C. Pillot, 2017). The availability of EV batteries for recycling depends on the lifespan of electric vehicles and achieved collection rates. In addition, potential use of EV batteries in second-life applications will delay the availability of these batteries for recycling. As the lifespan of EV batteries is roughly 10 years, growing LIB waste streams are expected in the near future. It is forecasted that around 150,000 EV batteries might be available for recycling in the EU in 2025 and the number would exceed 1 million in 2030 (in this scenario, batteries are assumed to reach end of life after 8 years and collection rates are estimated at 90 per cent for BEV and 50 per cent for PHEV) (Alves Diaz et al., 2018). LIB remains the choice of battery for the electric vehicles in the near future. The relative amount of cobalt in LIBs for automotive applications is expected to further decrease as the trend is shifting to low Co-containing cathode materials. This can negatively affect the profitability of the recycling process of EV LIBs.

2.3 Environmental impacts

Different battery technologies lead to various environmental impacts. Many of the battery types contain hazardous substances that can enter the environment if the batteries are landfilled, incinerated or improperly disposed of at the end of life (Stahl et al., 2018). For example, lead and cadmium are toxic elements and thus recycling efficiencies required for lead-acid and nickel-cadmium batteries are specifically addressed in the batteries directive. The use of cadmium is also prohibited in portable batteries with the exception of some special cases: medical equipment, emergency and alarm systems, cordless power tools. In addition, the use of mercury is prohibited in all types of batteries and accumulators (EU, 2006). Batteries also contain other hazardous substances that can cause safety risks when improperly used or disposed of, for example corrosive substances such as sulfuric acid in lead acid batteries and volatile and flammable substances such as liquid electrolytes in LIBs (Stahl et al., 2018).

Typically, the production of secondary raw materials causes lower environmental impacts when compared to the production of the primary raw materials. For example, for recycling of lead-acid batteries estimates have been presented that the use of secondary lead can reduce GHG emissions by two thirds when compared to the primary production of lead (Stahl et al., 2018). Concerning lithium ion batteries, there are several studies on their life cycle environmental impacts. However, the results show huge variation due to the assumptions used in the assessments, and furthermore, the majority of the studies focus on the production phase and only very few studies consider the end-of-life stage. Although LCA studies addressing the recycling stage are few and many of them are not satisfactory in terms of data quality, these studies suggest that production of LIBs using secondary metals from battery recycling is less energy demanding than extraction of primary metals. Thus, recycling and use of secondary materials is beneficial with respect to GHG emissions (Ellingsen et al., 2017). However, in the literature review by Romare and Dahllöf it is estimated that recycling of LIBs might not reduce GHG emissions especially when pyrometallurgy is used. This is due to the high energy demand of pyrometallurgical recycling and the fact that the recovered materials (Co, Ni, Cu) are in their elemental form and require further processing if to be used for battery manufacturing (Romare and Dahllöf, 2017). Recycling and use of secondary metals in LIB production can also minimize SO_x emissions when compared to extraction of primary metals (Dunn et al., 2015).

3 WEEE

3.1 Overview

Waste electrical and electronic equipment (WEEE, also called e-waste) is one of the fastest growing waste streams in the EU, growing at 3 to 5 per cent per year (Eurostat, n.d.). Electrical and electronic equipment (EEE) contain a complex mixture of materials, ranging from base metals to plastics, including also diverse substances that pose environmental and health risks if not treated adequately. EEE also contain precious metals and critical raw materials (CRMs). WEEE consists of a large variety of products, which can be grouped into six main categories: temperature exchange equipment (cooling and freezing equipment), screens, lamps, large equipment, small equipment and small IT equipment (Directive 2012/19/EU, Annex III).

Currently in the EU, only one third of WEEE is being reported as separately collected and appropriately managed. The directive on Waste from Electrical and Electronic Equipment (2012/19/EU) sets targets for the collection and preparation for reuse or recycling of WEEE. According to the directive, as of 2019 the minimum collection rate to be achieved annually shall be 65 per cent of the average weight of EEE placed on the market in the three preceding years in the Member State concerned, or alternatively 85 per cent of WEEE generated in that Member State.

The EC-funded Horizon 2020 project ProSUM examined the amounts of EEE placed on the market, stocks and WEEE generated in the EU28 + 2 countries (Switzerland and Norway) (Huisman et al. 2017). According to the ProSUM project, the overall amount of EEE placed on the market was 11.6 million tonnes in 2015, whereas the estimated amount of WEEE generated was 10.3 million tonnes. The ProSUM estimate of WEEE generation is much larger than the statistical amount of WEEE generated in EU28 according to Eurostat, which is ca 6 million tonnes (Eurostat, 2019).

The stock of EEE is significant, and it is increasing. Stock means products that are in use or stored in households, businesses and organisations before being discarded. It is estimated that about 129 million tonnes of EEE are in stock in Europe. According to Huisman et al. (2017), the average number of EEE products in EU28 + 2 countries is 44 products (plus 45 lamps and light fittings) or 248 kg per person, including all of the EEE in stock in households, businesses and public space (Figure 3.1).

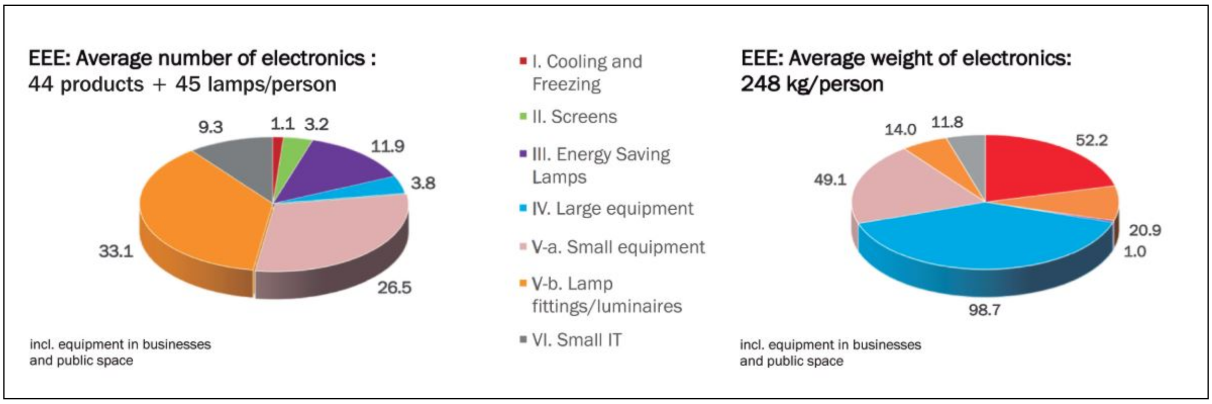


Figure 3.1 Average amount of electronics per person (Huisman et al. 2017).

The lifespan of EEE has shortened during the last decade, and the decrease in the residence time has targeted especially the appliances already having a short lifespan (e.g. mobile phones, digital cameras and laptops) (Bacher et al. 2017). In terms of shortened lifespans of EEE, there are also concerns about planned obsolescence, which means planning or designing a product with a limited useful life so that it will become obsolete or non-functional after a certain period of time (UCPD directive 2015, Oehme et al. 2017).

3.2 Current management and resource losses

The collection and recycling of WEEE is driven by the concept of Extended Producer Responsibility (EPR). EPR requires manufacturers and importers of products to be ultimately responsible for the end-of-life treatment of the products. WEEE is mainly collected through community waste collection sites or taken back by retailers (CRM recovery, n.d.). Reporting on collection and treatment of WEEE is regulated in Directive 2012/19/EU. The data on officially collected and recycled WEEE is reported to national registers by EEE producers and producer responsibility organisations. According to the ProSUM project, in 2015 only 3.8 million tonnes of WEEE (ca. 37 per cent of the WEEE generated) ended up in the officially reported amounts of collection and treatment (Huisman et al. 2017). According to Eurostat, in 2016 4.5 million tonnes of WEEE was collected, of which 4.1 million tonnes was recycled (Eurostat, 2019b). The collection rates of WEEE vary significantly between EU countries (CRM recovery, n.d.). The LIFE 2014 CRM recovery project estimated that if all poor performing EU countries could raise their collection rates in line with the current EU average, it would result in an additional 51 kilotonnes of WEEE being collected each year (CRM recovery, n.d.).

The flows of WEEE in Europe have been studied in the ProSUM project (Huisman et al. 2017) and CWIT (Countering WEEE Illegal Trade) project (Huisman et al. 2015). Part of WEEE is placed in the waste bin with municipal solid waste (MSW), which causes losses of valuable raw materials and contamination of other waste streams. Huisman et al. (2015) estimated that around 750,000 tonnes of WEEE end up in waste bins in Europe. The majority of WEEE ending up in waste bins consists of small household appliances, IT and telecommunications.

Complementary flows, which refer to all treatment and export that is not reported at Member State level by the official compliance systems, are significant in WEEE flows. Complementary flows include complementary recycling, e.g. recycling of WEEE with other waste streams (e.g. with metal scrap). Complementary recycling does not always meet the same efficiency and treatment standards as officially reported recycling. (Huisman et al. 2017). It is estimated that 2.2 million tonnes of mainly steel dominated consumer appliances is collected and processed under non-compliant conditions with other metal scrap (Huisman et al. 2015).

There is a gap between the total generation of WEEE and the combined amounts of WEEE officially collected, found in the waste bin and processed with metal scrap. In 2015, this gap was roughly 3.2 million tonnes, of which 1.7 tonnes was estimated to be processed within the EU; 950,000 tonnes of WEEE is estimated to end up in non-compliant recycling in EU. In addition to non-compliant recycling, the scavenging of valuable WEEE products (mainly relatively new and valuable devices like LCD screens, laptops and tablets) and components (such as printed circuit boards, cables and hard-disks) reduces the valuable material content of WEEE and diverts the material value to non-reported trading and complementary recycling. In 2015, the amount of scavenged and stolen parts was estimated to be 750,000 tonnes. There is also export of WEEE out of the EU. Huisman et al. (2015) estimated that 1.5 million tonnes of WEEE is exported out of EU. (Huisman et al. 2015) Figure 3.2 illustrates WEEE flows in different EU countries. In some countries (Cyprus, Malta and Romania) there is no WEEE at all that is collected and reported, whereas in some countries the recycling rate is 70 to 80 per cent (Bulgaria, Switzerland and Norway).

Table 3.1 WEEE streams (Huisman et al. 2017, Urban Mine Platform[3]).

Stream	Placed on the market (2015)	WEEE generated (2015)	Reported collection (2015)	Remarks
All WEEE	11.6 Mt	10.3 Mt	3.8 Mt	Only 37 % of WEEE is officially collected, the other 63 % was: - 0.75 Mt thrown in waste bin - 2,2 Mt collected with metal scrap - 0,95 Mt recycled under non-compliant conditions in Europe - 0.75 Mt scavenged for valuable parts - 1,5 Mt exported
Substreams				
Temperature exchange equipment	2 126 kt	1 607 kt	758 kt	Ca. 47 % of the waste generated is officially collected for recycling.
Screens	665 kt	1 347 kt	594 kt	Ca. 44 % of the waste generated is officially collected for recycling.
Lamps	75 kt	89 kt	22 kt	Ca. 25 % of the waste generated is officially collected for recycling.
Large equipment	423 kt	3 285 kt	1 283 kt	Ca. 40 % of the waste generated is officially collected for recycling.
Small equipment	3 681 kt	3 169 kt	801 kt	Ca. 25 % of the waste generated is officially collected for recycling. It is estimated that large amount of small WEEE (441 kt) end up in municipal waste.
Small IT	878 kt	846 kt	386 kt	Ca. 45 % of the waste generated is officially collected for recycling. It is estimated that large amount of small IT (119 kt) end up in municipal waste.

Figure 3.2 Collected and complementary WEEE Flows 2015 against WEEE Generated (100%) in percent, EU28+2 (Huisman et al. 2015).

[3] http://www.urbanmineplatform.eu/homepage

Box 1. Case mobile phones

- The service life of mobile phones is short (less than 2 years in developed countries) which results is large amount of waste that still may possess a great value. (Sarath et al. 2015);
- Mobile phones fall under category *Small IT and telecommunication equipment.* The official collection rate of this category was 45 per cent in 2015 (Huisman et al. 2017).;
- Average composition of a mobile phone: Plastic (59 %), Ceramics (16 %) Copper (15 %), Steel (3 %), Aluminium (2 %) Other metals (5 %). (Baxter et al. 2016);
- About 80 per cent of materials used in mobile phones can be effectively recycled. (Sarath et al. 2015);
- Consumer behaviour plays an important role in the recycling of mobile phones. Stockpiling of mobile phones in people's homes is known to be a particular issue. Awareness raising is important in order to increase the recycling rate of mobile phones. Also take-back systems of mobile phones should be improved by manufacturers and governments. (Sarath et al. 2015)

The main components of WEEE are metals, plastics, glass, rare earth elements (REEs) and minor metals (Tansel 2017). Most common metals used in EEE are iron, aluminium and copper, but in value, precious metals such as gold, silver and palladium generate largest shares of the equipment (Bacher et al. 2017). Base metals such as ferrous metals, aluminium and copper are recycled to a large extent, but not all metals can be effectively recovered from WEEE (Tansel 2017, Van Eygen et al 2016).

WEEE include several critical raw materials (CRMs), for instance antimony, beryllium, cobalt, germanium, gold, indium, lithium, natural graphite, niobium, silicon metal, silver and tungsten (Mathieux et al. 2017, Huisman et al. 2017). The ProSum project has estimated the amounts of selected materials in EEE in stock and WEEE (Table 3.2). Many critical metals or rare earth elements are not recycled, for example, because of low market prices that do not cover recycling costs, lack of recycling technologies at the commercial scale, or metallurgical limits to recovery processes (Thiébaud et al. 2018). For some elements that are used in EEE in small quantities (e.g., Au, Ag, Pd, Pt, Rh, Ir, Ru), economically feasible recycling can only be attained through processing at central facilities which may require cross-border transportation of WEEE (Tansel 2017).

Table 3.2 EEE placed on the market, WEEE generated and elements in-stock in EEE (2015) (Huisman et al. 2017).

	Placed on the market (t)	Stock (t)	Waste generated (t)
EEE	11.6 million	129 million	10.3 million
CRM			
Copper	270,000	4,100,000	330,000
Gold	26	230	31
Neodymium*	1,200	12,000	1,000
Indium	30	300	30
Silver	130	1,350	170

* High uncertainty

According to Van Eygen et al. (2016), the choice of the WEEE directive to focus on overall mass of WEEE in the recycling targets means that the recyclers can concentrate on the materials that are present in large amounts in the waste stream (e.g. ferrous metals or plastics) to achieve the recycling targets. This may lead to the fact that materials existing in small quantities, such as precious metals, can potentially be neglected, even though their primary production causes large environmental impacts and recycling of these materials could therefore avoid a large environmental burden as well as keep (critical) raw materials within the European economic system. (Van Eygen et al. 2017)

Glass can be highly recyclable without loss in quality or purity, but various impurities used in different EEE as well as metals and coatings that are difficult to separate create challenges for recycling glass from WEEE.

Previously, glass recovered from cathode ray tubes (CRT) displays was widely used for manufacturing new CRTs (glass-to-glass recycling), but nowadays the market demand for recycled CRT glass has declined due to the liquid crystal displays (LCDs) and plasma display panels (PDPs) replacing CRT displays. (Tansel 2017) Recycling of plastics from WEEE is discussed in section 4.2.4.

3.3 Environmental impacts

WEEE contain various hazardous metals and chemicals that can pose a threat to the environment and human health if WEEE is disposed of improperly or recycled in informal conditions. Hazardous components of WEEE include for example halogenated compounds such as polychlorinated biphenyls (PCBs) occurring in condensers and transformers, polybrominated biphenyls (PBBs) and polychlorinated diphenyl ether occurring in fire retardants for plastics. WEEE contain also many heavy metals and other metals such as arsenic, barium, beryllium, cadmium, chromium, lead, lithium, mercury and nickel. Hazardous components and chemicals in WEEE are presented in Table 3.3 (Garlapati 2016). The directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS, 2011/65/EU) aims to restrict certain dangerous substances used in EEE products that could be hazardous to human health and the environment, including substances that could hamper recycling.

Table 3.3 Hazardous components and chemicals in WEEE (Garlapati 2016, Kumar et al. 2017).

Component	Substance	Occurrence in e-waste
Halogenated compounds	Polychlorinated biphenyls (PCB) Polybrominated biphenyls (PBB) Polybrominated diphenyl ethers (PBDE) Chlorofluorocarbon (CFC) Polyvinyl chloride (PVC)	Condensers, transformers Fire retardants for plastics Cooling unit, insulation foam Cable Insulation
Radioactive substances	Americium	Medical equipment, fire detectors, active sensing element in smoke detectors
Heavy metals and other metals	Arsenic Barium Beryllium Cadmium Chromium VI Lead Lithium Mercury Nickel Rare earth elements Selenium Zinc sulphide	Light emitting diodes Getters in CRT screens Power supply boxes contains silicon controlled rectifiers and x-ray lenses Rechargeable Ni-Cd batteries, fluorescent layer in CRT screens, printer inks and toners Data tapes, floppy disk CRT screens, batteries, printed circuit boards Li-batteries Fluorescent lamps, alkaline batteries Rechargeable Ni-Cd batteries, electron gun in CRT screens Fluorescent layer Older photocopying machines Interior of CRT screens
Others	Toner dust	Toner cartridges for laser printers/copiers

The cross-boundary transport of WEEE from nations with strict environmental regulations to countries where the environmental regulations are not as strict and labour costs are lower (such as China, India, Pakistan, Nigeria and other developing countries) creates environmental problems and health risk concerns at these locations (Tansel 2017). In developing countries, WEEE is often treated in informal recycling methods such as open burning or acid leaching (Zhang et al. 2017). Informal WEEE recycling operations can contaminate soils, plants and groundwater samples with significant increases in heavy metal concentrations (Pradhan and Kumar 2014).

Recycling of WEEE is important in terms of avoiding negative consequences to environment and human health. Furthermore, WEEE include various precious metals and critical raw materials, the recovery of which can create energy savings and reduction of greenhouse gas emissions by reducing the demand for production of virgin materials.

An LCA study by Baxter et al. (2016) of the collection, transport and recycling of three different types of WEEE (refrigerators, LCD screens and mobile telephones) shows that small amounts of critical materials (refrigerants, precious/trace metals) are vital for the overall environmental accounts of the value chains. High-quality recycling ensures effective recovery of materials from WEEE. For all types of WEEE analysed, recycling created net environmental benefits in terms of global warming potential (GWP). The analysis of Baxter et al suggests that approximately 1 kg of CO_2 equivalent is saved by responsible recycling of a single mobile phone handset. Refrigerators contain refrigerant gases, the emissions of which result in a very large GWP. Therefore, proper handling of refrigerator waste and effective recovery of refrigerants is important in order to prevent leakage of refrigerants (Baxter et al. 2016).

Van Eygen et al. (2017) assessed the performance of WEEE recycling for the case of desktop and laptop computers in Belgium in 2013. According to the results, for desktop computers, 49 per cent of all materials and for laptop computers 39 per cent of all materials are effectively recycled. The rather low numbers are partly caused by the low recycling rate of plastics. If only metals (for which the recycling is possible at the considered end-processing facilities) are taken into account, for desktops, 87 per cent of metals are effectively recycled. For laptops this value is 85 per cent. According to Van Eygen et al. (2017), base metals such as ferrous metals, copper and aluminium are recycled to a large extent, while improvements can still be made in the recovery of precious metals.

4 Plastic waste

4.1 Policy relevance

The European Plastics Strategy aims to improve the economics, quality and uptake of plastics recycling and reuse, together with reducing plastic leakage into the environment (for example as marine litter), greenhouse gas emissions and the dependence on fossil fuels as a feedstock. Key objectives are also to keep the values of plastics in the economy and minimize waste. The Strategy is part of Europe's transition towards a circular economy, and will also contribute to reaching the Sustainable Development Goals, the global climate commitments and the EU's industrial policy objectives.

A special focus is on single-use plastics, which include products designed to be used once and then thrown away. By 2021 the EU will ban certain single-use plastics such as cutlery, straws, cotton swabs, plates, coffee stirrers and balloon holders. Other plastic items, such as beverage bottles, will have to be collected separately at a rate of 90 per cent by 2025. According to the new legislation, Member States will have to significantly reduce the consumption of plastic food containers and cups used for beverages, according to a timeline of six years after the new rules have been transposed.

The Packaging Waste Directive sets as minimum recycling target 22.5 per cent by weight for plastics counting exclusively material that is recycled back into plastics. The target is calculated by dividing the amount of packaging waste recycled by the total amount of packaging waste generated. Furthermore, the Waste Framework Directive sets obligations for separate collection of plastic wastes from municipal waste.

Reuse and recycling of plastics in construction and demolition waste, ELVs and WEEE also support achieving the recovery or recycling targets given in other legislation, even if no material specific requirements exist.

4.2 General overview of plastic waste amounts generated

Eurostat publishes information on plastic waste generated in all NACE activities, and separately also on plastic packaging waste. The figures differ due to different sources for data collection (plastic packaging waste are reported under the extended producer responsibility setting obligations on businesses in the packaging chain to supply data on the packaging that is handled and recovered and recycled). The plastic waste data cover both plastic packaging waste and plastic waste, but excludes, for example, fluff from light fraction from automobile or insulation materials containing plastic binders.

A summary of the reported waste amounts generated and amounts treated according to different sources is presented in Table 4.1. Compared to Eurostat data, significantly higher amounts of generated plastic waste are published by Plastic Europe (2018). Data in Table 4.1 indicate that the recycling and energy recovery rates are increasing, while the share of plastic waste going to landfills is decreasing. According to Eurostat data for plastic packaging waste, most member states (with one exception) met the recycling target of 22.5 per cent recycled plastic packaging waste (mean value 43%, variation range from 21% to 74%).

Table 4.1 Plastic waste generated and recycled in Europe according to different sources. Note! Plastic waste generated differs from the amount treated due to several reasons (data collection, stocks).

Source	Specification	2012	2015	2016
Eurostat				
Eurostat, wasgen	Plastic waste generation	15.0 Mt		17.6 Mt
Eurostat, wastrt	Plastic waste treated	10.3 Mt		10.6 Mt
	Material recycling	70 %		76 %
	Energy recovery	16 %		18 %
	Landfilling	13 %		4 %
Eurostat, waspac	Generated plastic packaging waste	15.1 Mt	15.9 Mt	16.3 Mt
	Material recycling	35 %	40 %	43 %
	Recovery (energy, others)	65 %	71 %	74 %
EEA waste model				
European Reference Model on Municipal Waste	Amount in residual waste (calculated based on amount residual waste and composition)		16.9 Mt	
	Selective collected, to recycling (reported by country)		10.6 Mt (63 %)	
Residual treatment	Energy recovery/Incinerated		6.54 Mt	
	Landfilled		4.62 Mt	
	Mechanical biological treatment		5.69 Mt	
Plastic Europe				
Plastic Europe 2013a, 2018	Plastic waste generated	25.2 Mt		27.1 Mt
	Collected for recycling	26.3 %		31.1 %
	Energy recovered	35.8 %		41.6 %
	Landfill	38.1 %		27.3 %

A recent study (2018) published by the Material Economic states that actually less than 5 million tonnes of plastic waste (corresponding to 5-10 per cent of the plastic demands) ends up being recycled (see Figure 4.1). The report explains that the difference is due to the fact that only part of the amounts collected for recycling is actually being recycled. Furthermore, collected amounts are a share of identified plastics waste rather than total plastics consumed. Total reported plastics waste in 2015 was estimated around 30 million tonnes, the actual demand was 49 million tonnes (2015). The report points out that a reason is the misclassification. According to a Swedish study only 50 per cent of plastics waste was actually reported as plastics waste in official statistics (Material Economics 2018). Another reason explaining the difference between demand for the plastics and generated plastics waste amount is the life span of plastic products (e.g. plastics in building appears as stock). In addition, only a part of the collected plastics is reprocessed due to mixed streams, contamination and the content of additives that hamper recycling. For high quality recycling, the plastics waste need to be separated to one type of polymer. In the report, it is concluded that the actual EU secondary plastics production as a share of demand is therefore closer to 10 per cent than 30 per cent.

Also several studies by the World Economic Forum (Neufeld *et al,* 2016), the Ellen MacArthur Foundation, Geyer (2017) and McKinsey & Company give the same message. For plastic packaging having the highest recycling potential, it is estimated that around 14 per cent is in a global perspective collected for recycling, but because of the costs of sorting and reprocessing actually only 5 per cent of material value is retained for use as further materials.

In the Plastic Factsheet published by the European Commission (2018), it is presented that only 6% of new plastic materials are from recycled plastics. Especially the Plastic Strategy (2018) aims to increase the share of recyclable plastics in new products. One challenge is the low price of virgin (and also recycled) materials which means that the recycling processes are not economically attractive. As a result, plastic wastes have been exported (in 2015 nearly half of the plastic packaging waste) outside Europe to places where cost structures (for example. labour cost) are lower.

The most common use of polymers by different sectors is illustrated in Figure 4.2. The packaging sector is dominating the use of plastic products, followed by the construction sector. Interesting to note is the typical life span of products linked to different sectors. Most of the packaging plastics become waste the same year they are produced, whereas construction plastics have a longer life span and will be demolished decades later. Figure 4.3 shows distributions for product lifetimes, as lifetimes may vary significantly across economies and also across demographic groups (Geyer 2017).

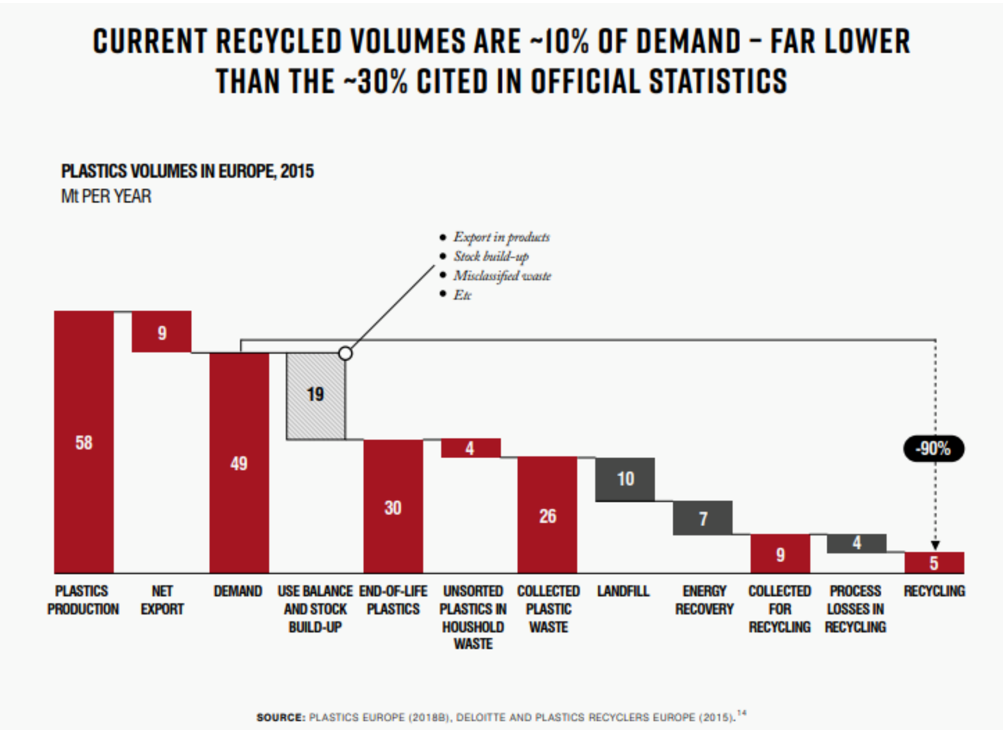


Figure 4.1 Scheme of loss of plastics during plastic waste collection and processing in 2015. (Material Economics 2018)

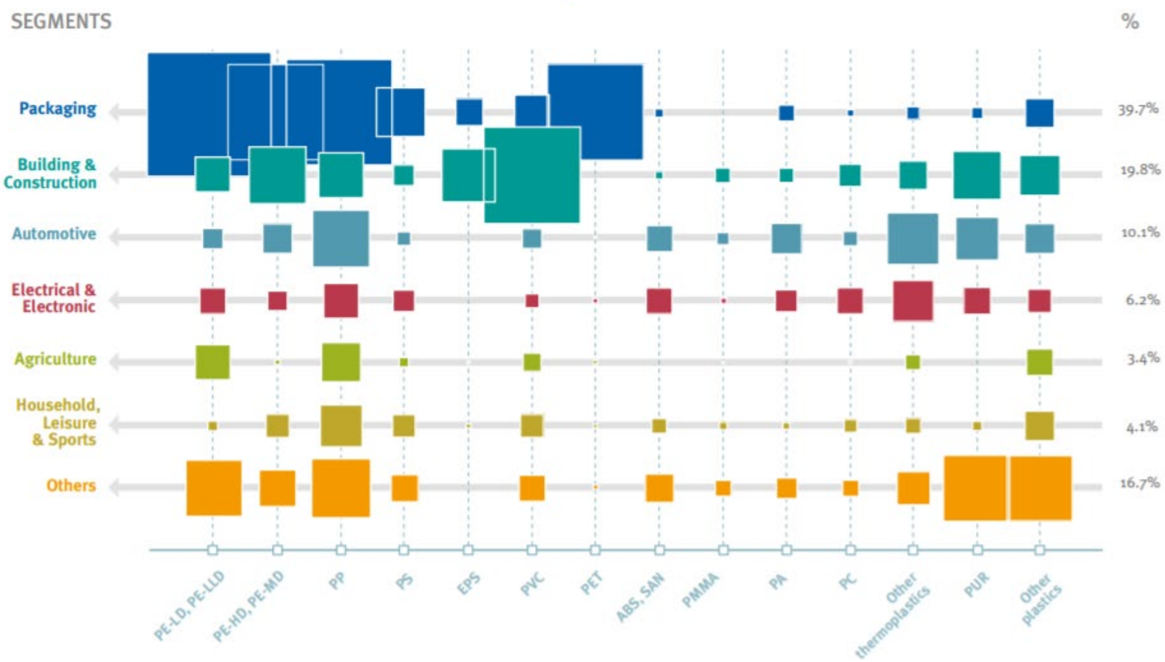


Figure 4.2 The share of different sectors in 2017 and also the main polymers in different activities. The total converted demand in 2017 was 51.2 million tonnes (Plastics Europe 2018a).

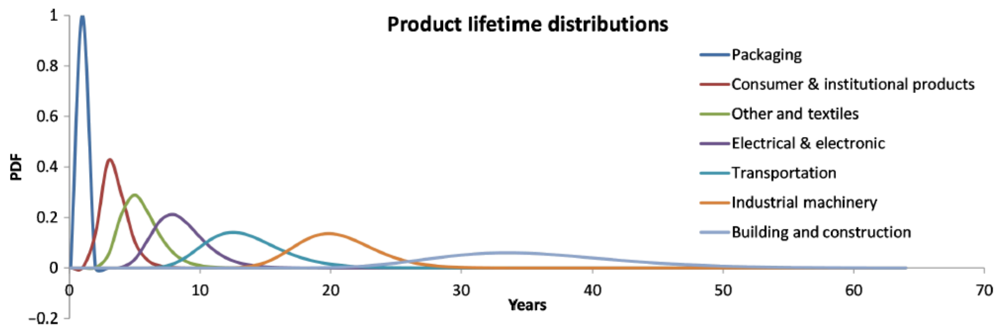


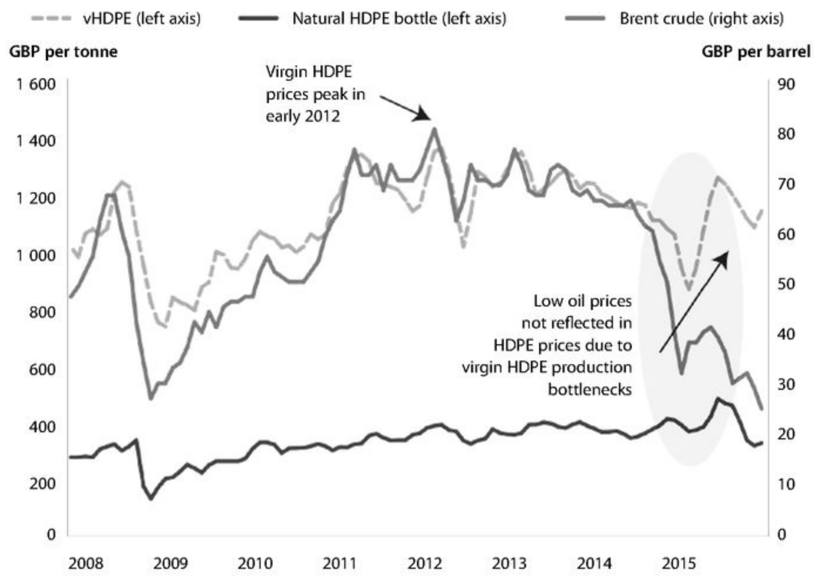
Figure 4.3 Product lifetime distributions for the eight industrial use sectors plotted as log-normal probability distribution functions. (Geyer et al 2017)

Several factors hampering the production of high quality secondary plastics have been brought up in recent reports. The main challenges are identified as follows (Material Economics, 2018):

- Plastic wastes are often heterogeneous streams containing different polymers and potentially also other materials (metals, paper). For a high quality recycling, different polymers need to be separated. The product complexity and also the collection systems are main barriers for cost efficient sorting and separation.
- Plastics often contain additives, colourants, plasticizers, stabilizers which makes recycling processes challenging. Furthermore, flame retardants, of which some are listed on ECHA´s list for substances of very high concern (SVHC), cause challenges in recycling, because of strict limits for content in recyclables.
- Plastics may be contaminated during use phase, e.g. by food waste, or by chemicals in contact with the plastics.

Especially for mechanical recycling of plastic wastes, all above aspects influence the recycling potential. In the future, chemical recycling (for example pyrolysis) is less critical of the feed and may offer a solution for converting polymers into monomers to be used in new products and also breaking down of contaminants and hazardous substances. However, the chemical recycling processes are still under development for several plastics streams. (Commission Staff 2019)

The lacking market for secondary plastics waste is due to the combination of the low quality, lack of quality standards and low demand. Also, the low price of virgin materials and costs for sorting and processing including investment costs, cause the products from secondary plastics to be typically used in low value categories such as garbage bags, flower pots and traffic cones. (Material Economics, 2018). Figure 4.4 illustrates how the price of recycled HDPE bottles follows the price of crude oil.



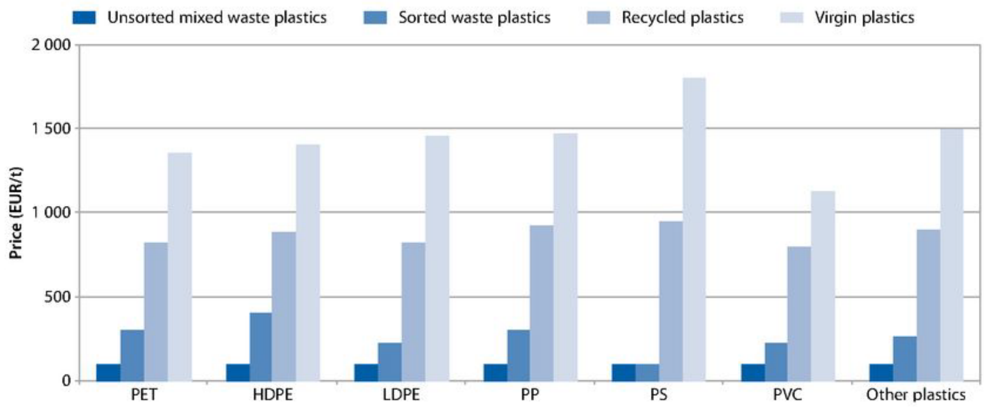
Source: WRAP (2016[51]), *Plastics Market Situation Report*, http://bit.ly/1o3IH0N.

Figure 4.4 Raw material prices of recycled HDPE bottles and crude oil (OECD, 2018a).

The difference in value of unsorted plastics compared to sorted and recycled plastics is illustrated in Figure 4.5. The value of unsorted waste plastics is less than 10 per cent of virgin plastics and the difference is highest for polystyrene. However, the sorting and processing costs for waste to vendible raw materials are significantly influencing the economy in recycling (e.g. in Figure 4.6 process costs estimated for 2017 as 439 euro/treated plastics). According to Material Economics (2018) the costs can be reduced by 16 per cent by following actions: designing products for recycling (e.g. material choices), scale of recycling and by creating more specialised but also regionally integrated recycling; adopting new technologies (Material Economics, 2018).

At the same time, by different actions such as improved technology or use of cleaner inflows, it is possible to reach a higher quality, which enables pricing closer to virgin materials. Also potential higher costs of virgin materials will improve buyers' willingness to pay for recycled materials; and better-functioning markets that reduce current commercial risk to buyers, thus incentivising the use of secondary plastics and investments in recycling capacity and innovation (Material economics, 2018) (Figure 4.6).

The Ellen MacArthur report (Neufeld *et al*, 2016) also paid attention to the existing incineration infrastructure assuming that the energy recovery possibility for plastics containing waste can effectively push higher-value mechanisms such as recycling out of the market.



Note: Data for unsorted mixed waste plastics is from analysis of WRAP Materials Pricing Report (2012-15).

Source: OECD, based on data from Hestin, Faninger and Milios (2015[74]), *Increased EU Plastics Recycling Targets: Environmental, Economic and Social Impact Assessment*, https://bit.ly/2w7mhoM.

Figure 4.5 The difference in value of unsorted plastics compared to sorted and recycled plastics (OECD, 2018a)

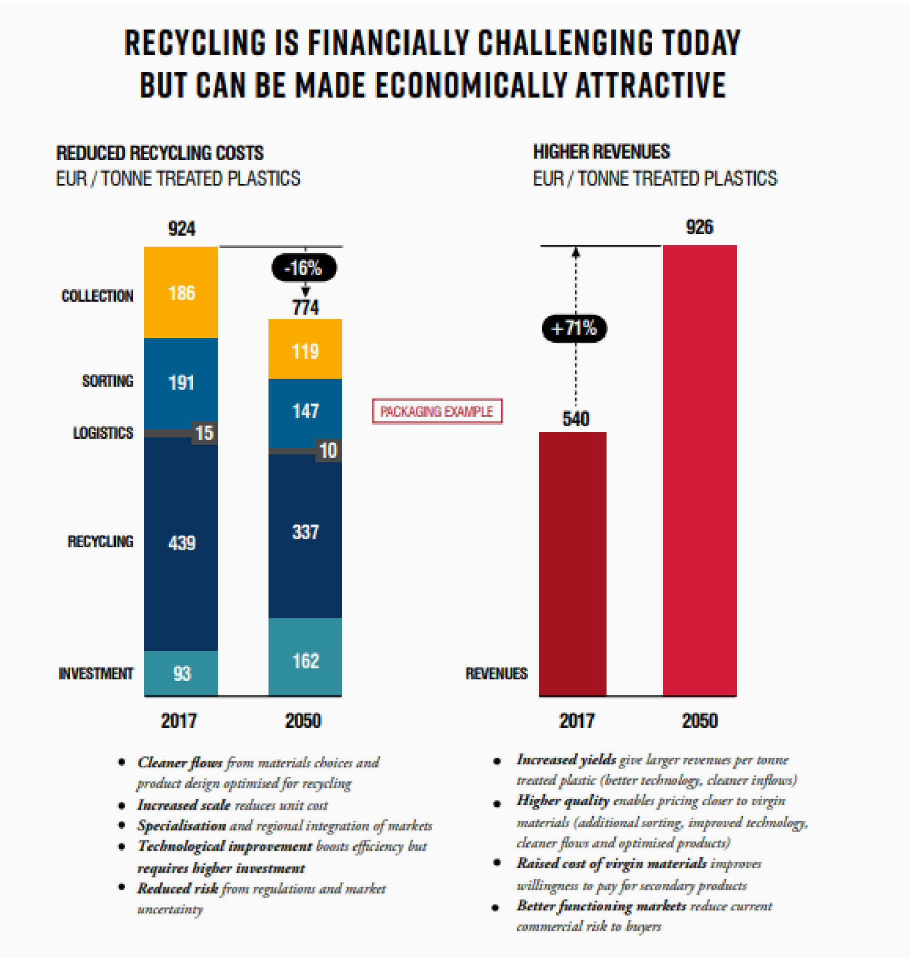


Figure 4.6 Cost structure of plastics recycling and actions to reduce costs and thus obtain higher revenues in recycling (Material Economics 2018)

In the following paragraphs, the recycling potential for a few selected sub streams in packaging, construction, electronics and the automotive industry will be further discussed. The selection of sub streams was made based on the recycling potential of the sub stream and the plastic share in these applications.

4.2.1 Packaging waste

The biggest demand for plastic is in packaging (see Figure 4.2). The demand was 20.3 million tonnes in 2017 and 20.0 million tonnes in 2016 (Plastics Europe 2018a, 2018b). The plastic packaging waste amount is 16.3 million tonnes in 2016 (see Table 4.1). The dominating polymers are polyethene, polypropylene and PET. Polymers in packaging waste are generally used in the following applications (e.g. UNEP 2018):

- PET (used in beverage bottles, food jars, some shampoo bottles and mouthwash bottles);
- HDPE (used in milk bottles, freezer bags, shampoo bottles, ice cream containers);
- LDPE (used in bags, trays, containers, food packaging film);
- Polypropylene (used in microwave dishes, ice cream tubs, potato chip bags, bottle caps);
- Polystyrene (PS) used in cutlery, plates and cups and expanded polystyrene (EPS) used in hot drink cups, insulated food packaging, protective packaging for fragile items;
- PVC used in rigid film, flexible film, closures, blisters, and presentation trays. Globally, PVC represents about 5 per cent of the plastic packaging market.

Plastic packaging waste is generated by both households and commercial sources (EU split: 62% / 38%, Hestin, 2015). In 2016, the separate collection rate of plastic packaging waste in the EU was 43%, or 7.0 million tonnes (Table 4.1). The remaining (over 9 million tonnes) of plastic packaging waste was disposed at landfills or incinerated with energy recovery. The separately collected plastic waste is transported to sorting facilities, where the waste is pre-treated (washed) and sorted into different plastic resins, melted and granulated. In the future, also plastics may be treated by chemical conversion where plastics are broken down to monomers or chemicals for production of new plastic products (Bacher *et al* 2016, Hestin, 2015, Material Economics 2018). In boxes 2 and 3 information on recycling and management of PET bottles and polystyrene packaging has been compiled.

Today there is increased focus on single-use packaging (e.g. food containers for burger boxes, sandwich boxes and one-person portion-sized food containers of fresh or processed food and some products made from expanded polystyrene). In the background report (Sherrington, 2017) to the Commission on single use plastics, the single use bottles are estimated to equal up to 1.7 million tonnes (amount extrapolated based on use of PET-bottles in Norway) or approximately 9 per cent of packaging production[4]. Furthermore, based on PRODCOM statistics, a calculation was also done to estimate the waste amount generated based on consumption of plastic carboys, bottles, flasks and similar articles with a capacity of 2 litres or less consumed in 2015. As a result, the waste amount was estimated to be of the magnitude of 2.5 million tonnes. From the PRODCOM statistics it was not possible to make a prognosis for waste from cups, straws, coffee stirrers and takeaway packaging. Estimations (presented by UNEP, 2018) have been made that the costs of removing all single-use plastics accumulating in the environment is higher than the costs of preventing littering today. For example, costs for cleaning shores and beaches in Europe are estimated to be 630 million euro per year.

Some important aspects which are related to plastic waste management are:

- the highest recycling potential of PET; HDPE/LDPE, PP (PET bottles, HDPE bottles, and post-commercial films — already high volumes of these streams are recycled today) (Ellen MacArthur Foundation, 2016);
- high quality recycling of polymers gives material savings compared to incineration (savings related to production of new materials);
- for at least 20 per cent of plastic packaging, reuse provides an economically attractive opportunity (Ellen MacArthur Foundation 2017);

[4] basis for calculation: 40% of consumption is used for packaging, equating to around 19 million tonnes

- with concerted efforts to redesign packaging and the systems for managing it after use, recycling would be economically attractive for the remaining 50 per cent of plastic packaging (Ellen MacArthur Foundation, 2017);
- it is estimated that without fundamental redesign and innovation, about 30 per cent of plastic packaging will never be reused or recycled. For example, small-format packaging, such as sachets, tear-offs, lids and sweet wrappers; multi-material packaging made of several materials stuck together to enhance packaging functionality, are likely to end up for incineration or landfilling after a short single use. (Ellen MacArthur Foundation, 2017)

Box 2. Case PET:

- Demand for PET was 7,4 per cent (3,9 million tonnes) in 2017 (Plastic Europe, 2018a)
- PET used in beverage bottles, has a higher recycling rate than any other type of plastic. However globally, close to half of PET is not collected for recycling, and only 7 per cent is recycled bottle-to-bottle. (Neufeld et al 2016). In Europe, it is estimated that on average of 57 per cent of PET bottles are recycled (Plastics Recyclers Europe 2018). The average recycled content in PET bottles in Europe has been around 11 per cent.
- Additives in plastics (either toxic or non-toxic) hamper the recycling process by contaminating the material stream, making recycling and the production of high quality secondary material either difficult or impossible (Watkins et al., 2017). One example is the opaque PET in plastic packaging increasingly used in cosmetic and dairy packaging, which has caused a degradation of the quality of recyclates (Zero Waste France, 2017). In the recycling process, it is difficult for recycling plants to distinguish the opaque PET from other materials such as (transparent) PET and HDPE. Yet unlike those materials, it is poorly recyclable due to its opacifier coating. (OECD, 2018b)
- It is important to consider environmental impacts 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. However, Hartline et al. (2016) found that in washing, 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 (EEA report 2018)
- A challenge in the recycling process of PET is that PVC can end up in the PET recycling stream, including (i) PVC bottles resembling PET bottles; (ii) PVC safety seals, labels, and sleeves that are used on PET bottles, and (iii) PVC liners that are used inside bottle caps and closures.
- The Single-use Plastics Directive under the umbrella of the plastics strategy sets goal that by 2025 at least 25 per cent recycled PET material is recycled in PET beverage bottles, and by 2030 at least 30 per cent (Commission staff working paper 2019)

Challenges in plastics packaging recycling include (Ellen MacArthur 2016 & 2017, Bachér 2016, Hestin 2015) the following:

- typically the waste stream is only recycled a few times (due to breakdown of polymers);
- in packaging waste, the sorting of different plastic types and the contamination from use hinder recycling;
- sorting of different plastic polymers is challenging due to lack of technology (similar “properties” such as densities). There are more than 50 different types of plastics and many plastic packaging products consist of more than one polymer type. This makes sorting and reprocessing more difficult than for other recyclable materials. For instance, it is not possible to recycle together a bottle and a food tray because they melt at different temperatures. Problematic plastics include black plastic food trays, which are used by many supermarkets. They are generally not collected as sorting machines are not able to detect them: the carbon black makes them invisible. If they are collected, they are likely to be rejected at the sorting plant.
- potential content of hazardous substances (plasticizers in PVC, flame retardants especially in electronics) hamper recycling.

Box 3. Case Polystyrene:

- Use of Polystyrene (PS) presents about 3 per cent of today's plastic packaging market. Its main applications in nonexpanded format are trays, cups, and bottles. While in expanded format it is typically used for disposable food packaging such as hot-beverage cups and clamshells, food trays and for cushioning and 'packaging peanuts' to protect objects during shipping.
- PS has very low recycling rates today — even if recycling is technically possible, there is a need for huge volumes to make processing more economic, which is a criteria seldom fulfilled. Furthermore, the plastic is typically contaminated, for example. by food in the case of food packaging. EPS is also very bulky (due to low density) with direct implications for collection and transport costs.
- Chemical conversion of plastics may offer a solution for high quality recycling in the future.

Reference: World Economic Forum, 2016

In the EU NewInnoNet project, different identified bottlenecks related to plastic packaging waste recycling were prioritized by an expert panel (Bachér 2016). Special focus was on actions that can be tackled by recyclers, because stakeholders in recycling industry can influence them. According to the results, the three most important actions with high impacts on recycling were identified and scored in the following order from most important to less important: "Improving the source separation", "Performance of separation/sorting technology", "Performance of downstream recycling technology". The project group also stressed the importance of political decisions for achieving a more efficient material recycling. In countries with high recycling targets, the recycling takes place. In countries with low recycling targets, export of waste outside EU may occur.

4.2.2 Plastic waste from construction

According to Eurostat, the plastics waste generated in the construction sector was 1.0 million tonnes (EU28, 2016) covering wastes from construction, renovation and demolition activities. Building and construction is the second biggest market for plastics in Europe, representing about 20 per cent of the overall demand in Europe. (Plastic Europe 2017b). The three big types of plastic are divided in the following application areas:

- Polyvinyl chloride (PVC) – for pipes and in building products such as window frames, floor and wall coverings, swimming-pools, cable sheathing and roofing;
- Polyethylene (PE) – for build pipes and other hardwearing products as well as to insulate cables;
- Polystyrene (PS) – used in a variety of ways from insulation foams to bath and kitchen units.

A summary of plastic waste from construction is presented in Table 4.2. Of the end-of-life plastics materials in construction, PVC has the highest recycling rate of 32 per cent. Information on PVC recycling is presented in Box 4.

According to a study published by the Finnish Ministry of the Environment (Kuittinen 2019), a significant part of the plastics used in buildings appears in paints, panels, boards, insulation materials used as resins and binding agents. The study focused on a selection of public owned buildings. For example, the share of plastics was estimated as 44 per cent in an apartment house of concrete and 37 per cent in house of wood. These plastics are difficult to separate and recycle.

Box 4. Case PVC

The main application for PVC in construction products are window frames and other profile applications, pipes and fittings, electric cables and conduits, flooring, membranes and waterproofing applications in coated fabrics and a variety of plastic linings.

The life span for PVC products in construction are typically several decades (up to 70 years or even hundreds of years). Some of the most widely used PVC containing products, e.g. pipes, might therefore never be collected as a waste if they are buried in the ground.

VinylPlus which is an European industrial initiative consisting of PVC manufacturers, additive producers and converters focusing on PVC waste collection and recycling, reports that almost 640,000 tonnes of PVC waste have been recycled in 2017 with the goal of 900 kilotonnes of PVC by 2025 and at least 1,000 kilotonnes by 2030. Based on recycled quantities, the three main types of PVC wastes recycled were as follows: 47.8 per cent windows and profiles, 19.9 per cent cables and 18.3% Flexible PVC. The increased demand for PVC products means that it is hard to reach a high percentage of recyclables in new products.

Substances of concern: Plasticizers such as Bisphenol A (BPA) and certain phthalates used in polyvinyl chloride (PVC), have already created concerns due to risks to human health and the environment. Over 95 per cent of the plasticizers are used in flexible PVC applications.

A characteristic in the construction sector is that the products remain in building for decades before they are removed (see also Figure 4.3). Construction products typically consist of a combination of materials, often attached by gluing, making the separation of materials for recycling difficult. A specific challenge is also the identification of the plastic materials suitable for recycling. Additionally the information of the material composition is lacking decades later. Chemicals (e.g. PCB, phthalates) used in the products may have been restricted later on and might therefore not be allowed in new products. For thermoset plastics (PUR, foams) mechanical recycling is not possible and the chemical conversion technology is still under development (lacking operating installations in Europe for other materials than polyolefins).

Table 4.2 Building and Construction Post Consumer Waste Generation 2014 (Europe EU 28+2) (source: Plastics Europe, 2017a)

Type of plastics	Total waste generation		Recovery					Disposal			
	in kt	in %	Total in kt	There of mechanical recycling		There of energy recovery		Total in kt	in %	There of Landfill in kt	There of Incineration without energy recovery
				in kt	in %	in kt	in %				
PE-LD	40	2,7%	31	11	27,5%	20	50,0%	9	22,5%	8	1
PE-HD	120	8,2%	85	27	22,5%	58	48,3%	35	29,2%	33	2
PP	60	4,1%	42	11	18,3%	31	51,7%	18	30,0%	17	1
PS	15	1,0%	10	1	6,7%	9	60,0%	5	33,3%	5	0
EPS	135	9,3%	85	9	6,7%	76	56,3%	50	37,0%	47	3
PVC	840	57,6%	520	270	32,1%	250	29,8%	320	38,1%	310	10
Others	248	17,0%	197	17	6,9%	180	72,6%	51	20,6%	46	5
Total	**1.458**	**100,0%**	**970**	**346**	**23,7%**	**624**	**42,8%**	**488**	**33,5%**	**466**	**22**

4.2.3 End-of-life vehicle

According to Eurostat, end of life vehicles generated 6.36 million tonnes of wastes in 2016 (EU 28). The estimated total plastic waste amount in the automotive sector has (in an EU NewInnoNet project) been estimated to be around 1.2 million tonnes per year.

The average share of plastics in vehicles has increased in the last 50 years and is expected to reach 18 per cent by 2020 (Miller 2014, Kearny 2012), as the vehicle weights have been reduced. Plastics are used in various parts of vehicles such as the interior trim, seating, bumpers, upholstery, electrical components and dashboards (CBI, 2016), and the main polymers used are polyvinyl chloride, polypropylene and polyurethane rubber (Kanari 2003). Only a few plastic parts actually are recycled: typically these are the fascia (or "bumpers"), dashboards, and battery casings (Miller 2014). The plastics materials (e.g. seats, interior plastic parts), especially in old vehicles, may contain flame retardants which restricts recycling (Havre 2015).

Recycling of end-of life vehicles is governed by metal recycling which constitutes the main part of the vehicle (Kearny. 2012). The recycling system and technologies for metals have been well established for decades. Scrap metal also has a monetary value as input material for production. For polymer-based products, recycling is still lacking on a larger scale. Recycling of plastics requires new innovations and also a traceability system. The main challenges are the low price of virgin polymers and the volatility in polymer prices. Plastics from end-of-life vehicles are often downcycled to other applications due to material degradations (see box 5 on bumpers). Furthermore, there is a knowledge gap between manufacturers, consumers, and end-of-life facility operators. Plastics in automotive applications are heterogeneous, have strong connections to other plastics, and are thus difficult to liberate for recycling. Materials are often contaminated or they contain hazardous substances, for example flame retardants in PU foam which has been downcycled for use in carpet underlay, or carbon fibres which have been used in the construction industry as fillers for artificial woods and asphalt. (Miller, 2014)

During the dismantling process of car components prior to the demolition process, bumpers and fuel tanks are typically removed and therefore become available for reuse or recycling. The front and rear "bumper covers" are to some extent sold for reuse (Miller 2014). In Europe, the total amount of bumpers can be estimated to around 108 kilotonnes based on deregistered vehicles (around 12 million vehicles per year).

The plastic fraction (excluding bumpers, fuel tanks and batteries) ends up in the light fraction of the shredder waste, which is the residue after metal recovery from vehicles, comprising of a mix of plastics, rubber, wood and other non-metal residuals. It typically contains around 30 per cent of plastics (Table 4.3). According to Eurostat, about 680 kilotonnes of shredder waste was generated in 2016 of which 40% was landfilled, 31 per cent incinerated with energy recovery and 29 per cent was recycled.

Table 4.3 Composition of automotive shredder waste (compiled from different sources in Zevenhoven & Saeed, 2003)

Material	**Share of plastics in the light fraction of automotive shredder waste (weight %)**					
	a	**b**	**c**	**d**	**e**	**f**
Plastics	30-48	20	21.5	41		33
Plastics (foam)						15
Plastics (including rubber)					83.1	
Elastomers (including rubber)	10-32	20	5.3	21	2.6	18

Box 5. Case: Bumpers

A challenge in bumper reuse is that manufacturers in the automotive industry have different material specifications for the same types of parts. Dismantled bumpers can often not replace bumpers in new cars due to product requirements. Also the electrical wiring attached to bumpers needs to be removed before the bumper can be reused and there is a risk that the dismantling process may damage the bumpers.

Recycling of polypropylene bumpers has been studied using a physical recovery method to separate different plastic materials, based on translucency, density, or solubility. The efficient removal of the coatings on bumper surfaces presents a technical difficulty in the bumper recycling process. Furthermore, in recycling of bumpers into new bumpers, there is the need for addition of considerable amounts of virgin matrix.

In a pilot study in the US (Plastic Industry Association, 2018), several car manufactures investigated the possibilities for recycling of bumpers. The recyclers participating in the study were able to create very high-quality polyolefin pellets at a lower cost than prime polymer. While the recycled polymer could not be a direct replacement for virgin polymer in a high-demand application like bumpers, the material exhibits very good properties for non-critical applications on vehicles or feedstock for manufacturing in other industry sectors.

References: Miller, 2014; Zhang, 2014; Luda 2013

In conclusion, plastics play important role in the automotive industry but a lot of effort is still required to ensure that their use is sustainable. This requires co-operation and knowledge transfer in the value chain of the automotive industry. Mindset of sustainable design needs to be adapted, which includes for example reducing the number of type of materials and selecting materials with easy-to-recover properties. Establishing applications and sound market for recyclates is a prerequisite for keeping the materials in reuse/recycle loop, and energy recovery should be implemented when material utilization is not possible. (Miller, 2014)

4.2.4 Plastics in electronic wastes

According to ProSUM project, the total Waste from Electric and Electronic Equipment (WEEE) accounts annually for 10.3 million tonnes of which 2.4 million tonnes is plastics. Even 129 million tonnes EEE are estimated to be in stock in households, businesses and public space. The EEE in stock contains 26.5 million tonnes of plastics. (Huisman et al. 2017)

In recycling of WEEE, as for ELVs, the main focus is on metal recovery. Plastics waste is used as fuel in the metal recovery processes. Plastics in WEEE not sent to metal smelters are sent to specialized recyclers where plastics are separated by type, compounded and then reprocessed into products. There are both economic and technical challenges in the mechanical recycling of plastics in WEEE (several steps needed, volumes). The main challenge is the large number of different types of plastics (Table 4.4) and the significant use of black plastics in electronic and electrical equipment. According to plastic recycling companies (2016), technology exists to recycle over 50 per cent of the plastics from WEEE into Post-Consumer Recycled (PCR plastics). The plastics which cannot be recycled as material, can be used for energy recovery. The total demand for plastics for the production of EEE accounts to 2.5 million tonnes per year. The actual use of PCR plastics for the production of new EEE has been proven in a significant number of cases.

Table 4.4 Average composition of WEEE plastics for recycling

Plastics in WEEE	
ABS	24 %
HIPS	27 %
Polyolefins	7 %
PC and PC-ABS	7 %
Other plastics including BFR	29 %
Parts and metals	4 %
Other (mainly wood)	2 %

Special attention in WEEE management is put on small device applications (SDA). A characteristic of SDA is the low weight and small size. Therefore, SDAs are often stored in homes or to some extent misplaced with municipal waste. For example, mobile telephones represent a particular challenge with respect to stockpiling. Several studies indicate that high percentage of phones are retained at end-of-life by users. (See chapter 3, box 1) The share of plastics is reported to be around 30 per cent in small device applications (SDA). According to the Urban Mine Platform developed under the ProSUM project, the WEEE SDA in 2015 accounted for 3.1 million tonnes (Huisman et al. 2017) which equals to 0.93 million tonnes WEEE-SDA plastics (assuming plastic share as 30%). This amount does not include the stockpiling in homes.

Particularly vacuum cleaners, coffee machines and old TV casings have been mentioned as sources of plastics for recycling, because these products do not contain many types of polymers and have a low content of hazardous substances.

A special concern related to recycling of plastics from electronics are the flame retardants, which have been added to polymers used for computer, electronics and electrical equipment in order to improve fire safety of consumer products. Hazardous substances – heavy metals and brominated flame retardants – have been found especially in plastics derived from certain types of product (TVs, monitors and domestic telecommunications equipment) (Baxter et al 2014). Especially brominated flame retardants, some of which are listed as persistent organic pollutants, have raised concern. This sets requirements for identifying plastics containing hazardous substances. Flame retardants have been found in products manufactured from recycled plastics. (Dutch ministry, 2018). EU legislation on hazardous substances (POP regulation, ECHA's list of substances of very high concern) sets the need for traceability of materials in order to guarantee that no hazardous substances are present in the recycled materials. This makes it very difficult to find markets for certain materials.

The high amount of WEEE products containing compounds that are unwanted in recycled plastics needs to be tackled at the production stage. This is difficult as most WEEE products are manufactured in Asia and producers are not bound by the same regulatory standards or the same incentives and motivations as European actors. (Baxter et al 2014)

Manufacturers in US mainly presenting electronic products (laptops, household electronics...) initiated a study aiming to create an overview of the challenges involved in creating closed loops for engineering plastics sourced from electronics and cars (Vlugter, J. 2017). According to the study, the scale and effectiveness of collection activities, the lack of a market for recyclates and the limited skills and collaboration between value chain partners are factors hampering the closed loop recycling of plastics. Brand owners can help to develop markets for recycled plastics by designing the products in a way that takes into account the aesthetic limitations of recycled plastics, re-evaluating critical material requirements and developing step-by-step processes for scaling the application of recycled plastics in their organisations. Brand owners can also take a role as coordinators of a value chain in order to support closing the loop of plastics recycling.

Additionally Baxter (2014) pointed out, as a key challenge in the recycling business, the uncertainties in interpretation and measurement of restricted substances and to some extent also the changing legislation for processing. This lack of predictability influences the investments in the sector.

4.3 Environmental impacts

The key environmental benefit from plastic recycling is the contribution to reduced CO_2 emissions. Oil is the basic feedstock of plastics. About 5 per cent of crude oil is used in plastics manufacturing (Plastics Europe 2018). Recycling of plastics can reduce the use of raw materials and energy in the virgin plastic production process and also the greenhouse gas emissions originating from waste plastics incineration.

The savings in CO_2 emissions in different recycling options is visualized in Figure 4.7. On average, it is calculated that each tonne of plastics produced results in 2.5 tonnes of CO_2 emissions from the production process alone. In addition, carbon captured in the plastic material contributes to another 2.7 tonnes of CO_2. The release of the captured carbon depends on how plastics are treated at end of life. In landfills (or if plastics are released into the environment), that process occurs slowly, as the degradation of plastics takes many (potentially, hundreds of) years. However, many countries have banned landfilling of organic wastes and therefore plastic waste not directed to recycling is incinerated for energy generation, which leads to the immediate release of all captured carbon as CO_2. (Material Economics 2018, Neufeld 2016)

In plastic production, emissions can be lowered by improving energy efficiency and by using renewable energy sources (to 3.7 tonnes CO_2 per tonne plastics). In comparison: in low grade mechanical recycling (involving steps with cleaning, re-melting and upgrading) the CO_2 emissions are 1.4 tonnes CO_2 per tonne plastics, whereas in chemical recycling (for example by pyrolysis where plastics are broken down to monomers or chemicals which can be used as raw materials for new products) the calculated CO_2 emission is 1.0 tonne CO_2 per tonne plastics. Assuming that potentially 56 per cent of plastics volume could be mechanically recycled or reused and another 11 per cent could be recycled through chemical recycling techniques (such as pyrolysis and depolymerisation), this would roughly reduce emissions from 233 to 144 million tonnes CO_2 per year, compared with producing new plastics and incinerating them at end-of-life. (Material Economics, 2018)

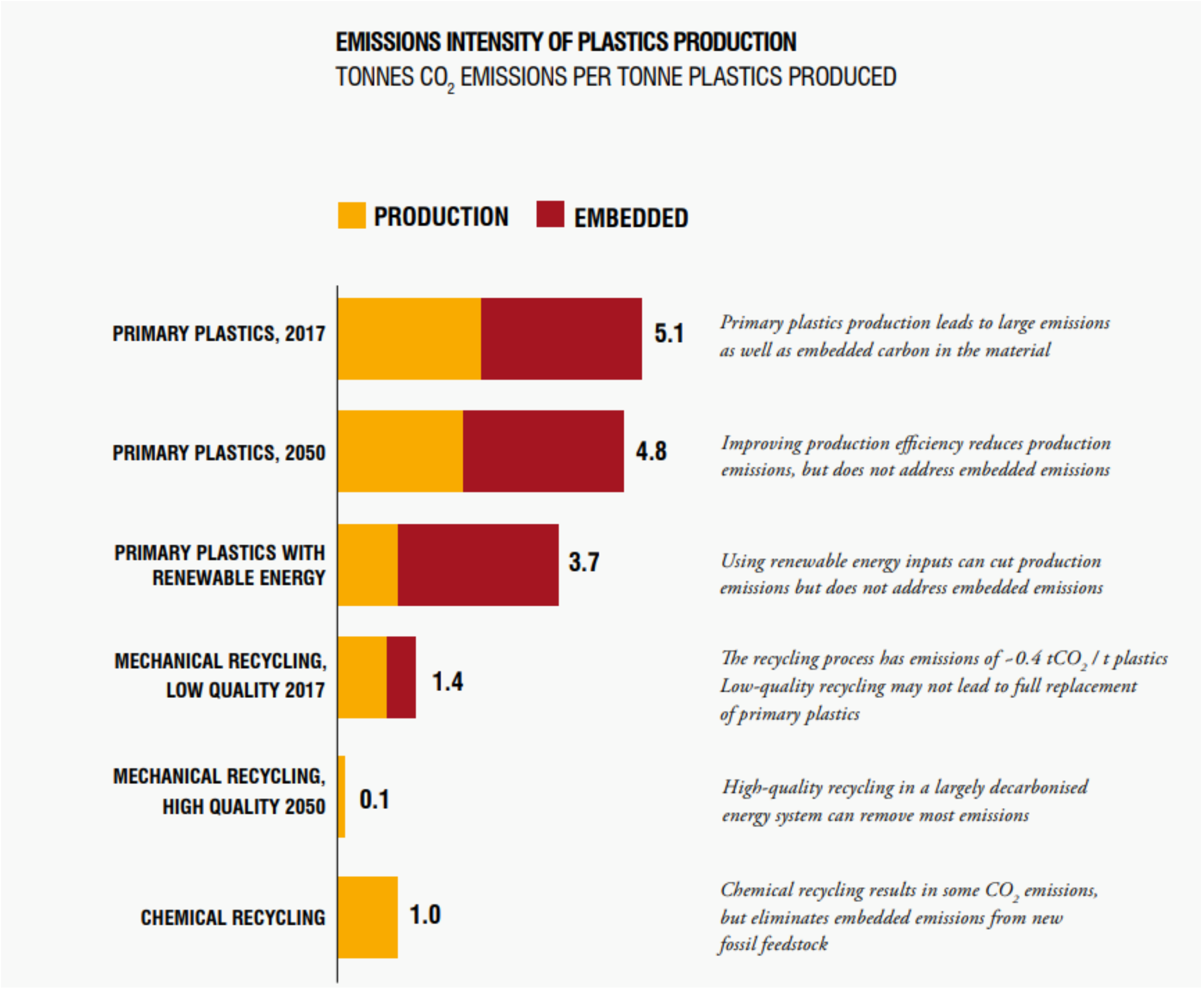


Figure 4.7 Comparison of CO_2 emissions in different recycling option in relation to primary production (Material economics 2018).

Besides greenhouse gas emissions, littering problems arising from waste plastics would also be reduced if plastic waste is collected and recycled.

In some applications, recycled plastics waste may cause release or degradation of plastics to microplastics, which are spread to the environment (for example seas). Determining the environmental effect of the interventions that prevent plastic packaging ending up as litter on land (beaches) or in water is not possible because of insufficient data and the absence of a methodology to measure.

Especially WEEE plastics contain hazardous substances (for example flame retardants) that limit the actual recycling potential. Wastes containing hazardous substances listed as persistent organic pollutants needs to be destroyed at high temperatures. During incineration/combustion of the plastics halogenated flame retardants can produce toxic gases which are spread to the environment if thermal treatment is not fulfilled. Also residues of flame retardants can end up in the solid fractions in case of insufficient incineration conditions.

5 Textile waste

5.1 Overview

In 2015, the European Commission adopted a Circular Economy Package, which includes revised legislative proposals on waste to stimulate Europe's transition towards a circular economy. The proposals included targets of 65 per cent of municipal waste to be recycled by 2030, maximum 10 per cent of municipal waste may be sent to landfill by 2030 and a ban on landfilling of separately collected waste. Although, there were no specific targets for textiles in the original proposal, the European Parliament voted in March 2017 to include a requirement that countries must ensure that systems are in place for the separate collection of (discarded) textiles by 2025. It also voted to increase the household waste recycling target to 70 per cent including 5 per cent preparation for reuse (Watson et al 2018).

According to Beton et al (2014) the total EU27 consumption of textiles in 2007 was estimated at 9.55 million tonnes of textile products (giving 19.1kg/capita), of which 6.75 million tonnes were clothes and 2.79 million tonnes were household textiles. No recent number for the EU28 were found.

Furthermore, the EU28 is a net importer of textiles: 8.8 million tons in 2018. Import of textiles[5] is equal to 14.5 million tons, while the export is only 5.7 million tons. The net import is equal to 17.3 kg per EU28 capita. The value of the import stream is 139 billion euro, compared to an export value of 61 billion euro. The net import is equal to 152 euro per EU28 capita (Eurostat, 2019)

The top 10 countries from which the EU28 imports (in physical quantities), represent already 85 per cent of the total import quantity. 37 per cent of the import is from China, followed by Turkey (11 %), Bangladesh (10 %), India (9 %), Pakistan (5 %), Vietnam (3 %), Korea (3 %), Indonesia (2 %), Cambodia (2 %) and the United States (1 %).

The top 10 countries to which the EU28 exports (in physical quantities), represents 55% of the total export quantity. As this share is remarkably lower, it shows that import is more concentrated compared to a more fragmented export. 10 per cent of the export goes to China, followed by Turkey (9 %), United States (8 %), Pakistan (5 %), Switzerland (4 %), Russian Federation (4 %), Tunisia (4 %), Morocco (4 %), India (4 %) and Ukraine (3 %).

Similar results can be seen from Euratex (Table 5.1). The total Extra-EU28 import of textiles amounts to 116 billion euro, while export sums up to 52 billion euro. Main suppliers of textile and clothing are Bangladesh, China, Turkey, India, Cambodia, Pakistan and the United States. Extra-EU28 customers of textiles and clothing are Switzerland, United States, Russia, China, Turkey, Morocco and Hong Kong.

[5] Textiles defined by the Harmonized Commodity Description and Coding System (2012) chapters 50 till 67 (section XI and Section XII).

Table 5.1 EU-28 main trading partners in textile-clothing (source Euratex, key figures 2017)

EU28 - main trading partners in textile-clothing*

mio Euro	2016		2017	
Textile customers	United States	2 618	United States	2 605
	China	1 976	China	2 064
	Turkey	1 667	Turkey	1 773
	Morocco	1 459	Morocco	1 557
	Switzerland	1 408	Switzerland	1 398
	share top 5 countries	41,9%	share top 5 countries	41,1%
	extra EU28	21 776	extra EU28	22 846
Textile suppliers	China	9 762	China	10 087
	Turkey	4 914	Turkey	4 930
	India	2 654	India	2 815
	Pakistan	2 407	Pakistan	2 559
	United states	1 101	United states	1 161
	share top 5 countries	71,8%	share top 5 countries	71,7%
	extra EU28	29 027	extra EU28	30 056
Clothing customers	Switserland	3 442	Switserland	4 748
	United States	3 121	United States	3 097
	Russia	2 061	Russia	2 279
	Hong Kong	1 945	Hong Kong	1 977
	Japan	1 369	Japan	1 394
	share top 5 countries	41,1%	share top 5 countries	46,5%
	extra EU28	29 027	extra EU28	29 027
Clothing suppliers	China	27 774	China	27 212
	Bangladesh	14 965	Bangladesh	15 311
	Turkey	9 530	Turkey	9 580
	India	5 136	India	5 017
	Cambodia	3 404	Cambodia	3 694
	share top 5 countries	74,9%	share top 5 countries	74,1%
	extra EU28	81 222	extra EU28	82 038

* Textiles & Clothing from HS chapters 50 to 63
** Including also textiles from HS 30, 39, 40, 48, 68, 69, 70, 96

5.2 Consumption, current management and resource losses

EU consumers discard about 5.8 million tonnes of textiles every year according to the European commission. (Friends of the Earth, 2013).

No overall data could be found for separate collection rates for textiles across the EU as a whole, either as a share of textiles put on the market each year, or in kg per capita. GFA & BCG (2017) claim the separate collection rate to reach 20 %, but this is based on figures given in (Beton et al., 2014), which itself uses data from Textile Recycling Association (2005) based on the OUVERTES study for seven countries - France, the UK, the Netherlands, Germany, Poland, Spain and Belgium – using 2004 data or earlier, so these figures can no longer be trusted.

Recent studies have been carried out in several countries that estimate collection rates either in kg per capita or in shares of new textiles placed on the market (Table 5.2). Such studies are known from Denmark, Germany, France, Flanders, Italy, the Netherlands, Sweden and the UK.

Table 5.2 Estimated separate collection rates for clothing and household textiles in eight EU countries (Source: Watson et al. (2018)

country or region (data year)	Flanders (BE) (2013)	Germany (2013)	Denmark (2010)	France (2016)	Italy (2015)	Netherlands (2012)	Sweden (2013)	UK (2010)
Consumption (ktonnes)	-	1347	89	600	881	240	121	1693
Consumption (kg/capita)	-	16,7	16	9	14,5	14	12,6	26,7
Separate collection (ktonnes)	53	1011	39	214	133	89	23	619
Separate collection (kg/capita)	8,1	12,5	7,4	3,2	2,2	5,4	1,4	11
Share of quantity placed on the market (%)	-	75%	44%	36%	11%	37%	19%	31%

The collection of used textiles was dominated by charities. Recently however, municipalities and high-street clothing brands are increasingly engaging in these efforts, driven by waste prevention programs and environmental considerations (ECAP, 2018[6]). The relatively high value of separately collected textile waste is also an important driving factor regarding separate collection. This can be seen in the Figure 5.1, which is based on the materials pricing report (WRAP, 2019[7]).

[6] http://www.ecap.eu.com/wp-content/uploads/2018/07/ECAP-Textile-collection-in-European-cities_full-report_with-summary.pdf
[7] http://www.wrap.org.uk/content/materials-pricing-report

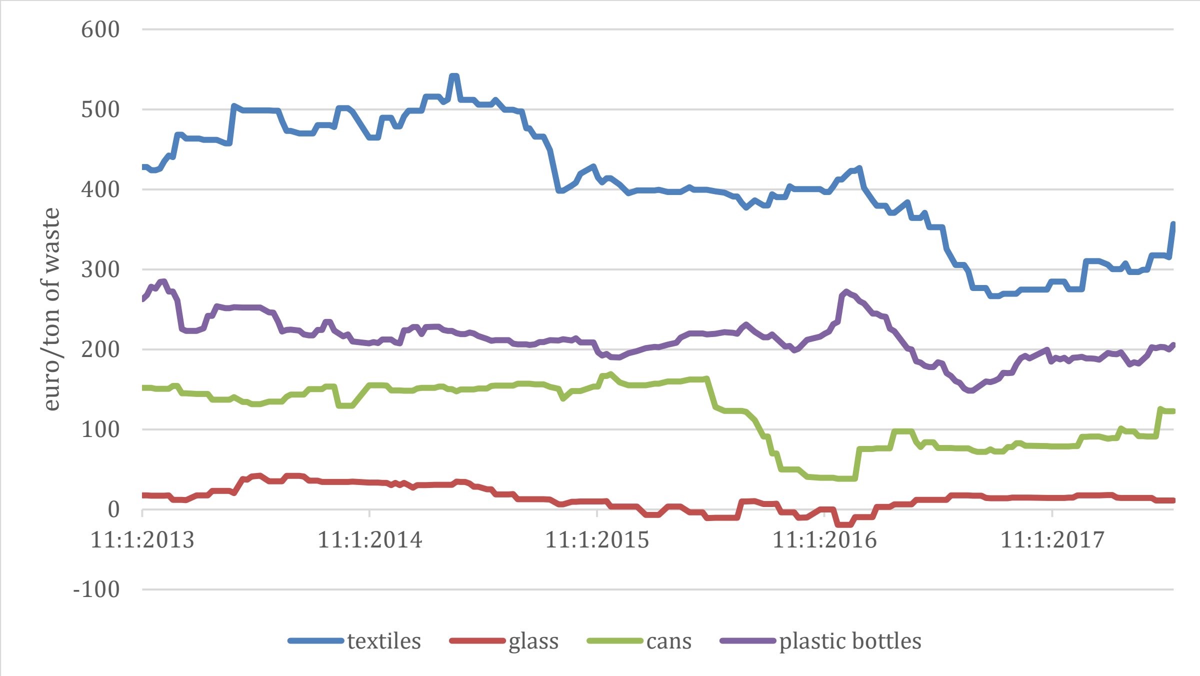


Figure 5.1 Value of separately collected textile waste own calculation, based on average prices of material flows. (Source: WRAP, 20 19)

Separately collected textile waste is reused or recycled by charities or industrial enterprises. Of the reusable clothes collected in the Nordic Region, approximately 90 per cent are exported and sold on foreign markets, typically in Eastern Europe, Africa and Asia (Watson et al., 2016; Palm et al., 2014a). The non-reusable fraction is downcycled, for example as rags, upholstery filing or insulation, or is incinerated. Approximately 1 per cent of textile waste is recycled into new clothes, since technologies that would enable recycling clothes into virgin fibres are only starting to emerge (Šajn, 2019).

Similar shares, though a bit more optimistic regarding reuse and recycling, are given in the following infographic[8] (Figure 5.2).

[8]https://globalfashionagenda.com/wp-content/uploads/2017/04/GFA17_Call-to-action_Poluc-brief_FINAL_9May.pdf

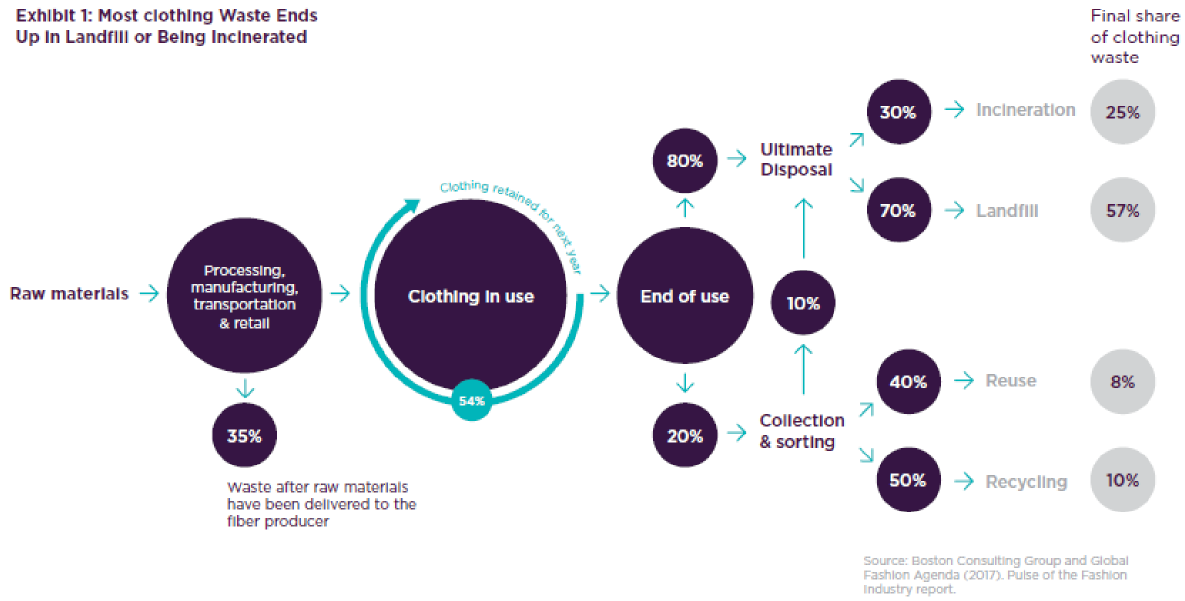


Figure 5.2 : Overview of production, use and end-of-life of clothing. (source : Ellen MacArthur Foundation, "A New Textiles Economy: Redesigning fashion's future", https://www.ellenmacarthurfoundation.org/our-work/activities/make-fashion-circular/report)

Studies on textile collection and reuse recycling have pointed out that only a minor proportion of collected used garments are actually reused in Europe (Watson et al. 2016). Behavioural research (WRAP, 2017) indicates that the vast majority of purchases from European citizens were of new clothes (Figure 5.3). Only a small amount of people considered buying second hand, an even smaller amount of people actually bought second hand.

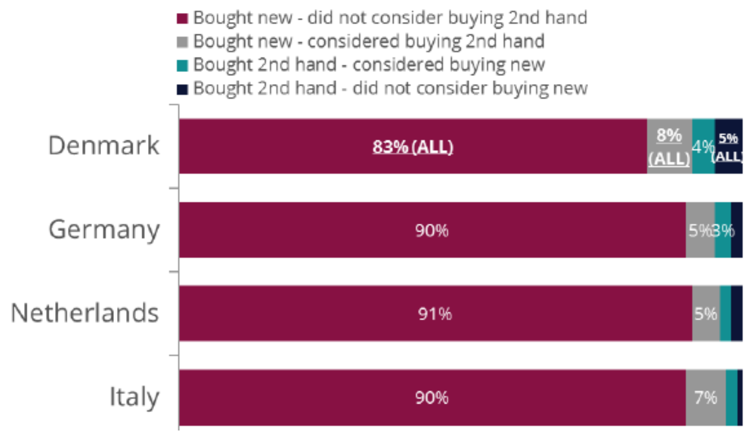


Figure 5.3 New and second hand clothing purchasing decisions (source : WRAP, 2017)

The average number of times clothing is worn decreased significantly the last 15 years, while the sales (in number of items) is going up (Figure 5.4). This trend in number of times worn isn't seen in the EU28 (Figure 5.5). However, Sajn, 2019 mentions the rise of fast fashion

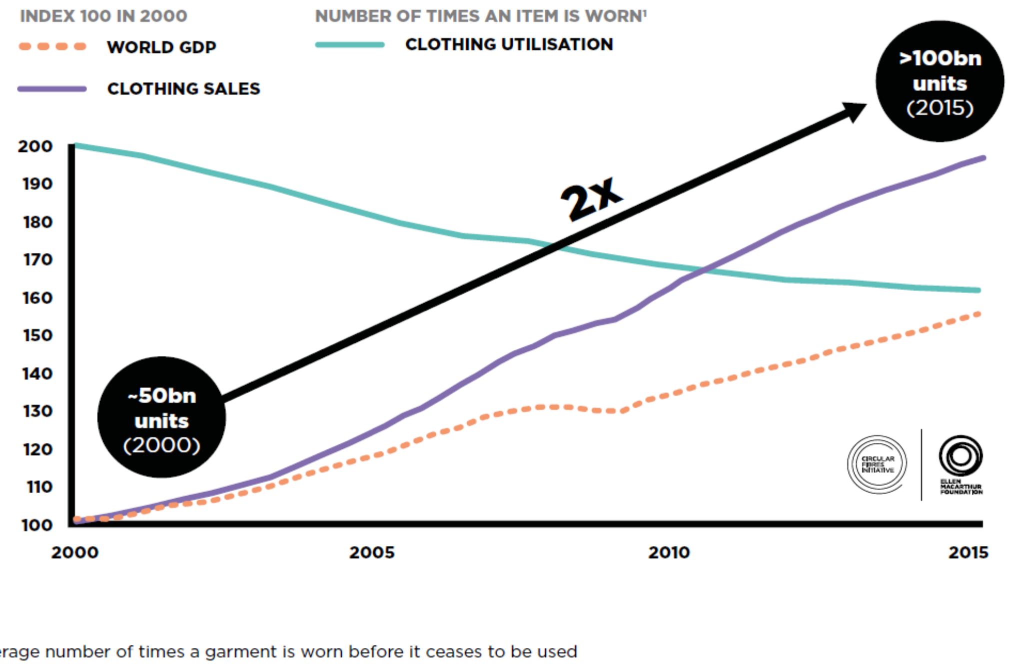


Figure 5.4 Growth of clothing sales and decline in clothing utilisation (source : Ellen MacArthur Foundation, "A New Textiles Economy: Redesigning fashion's future", https://www.ellenmacarthurfoundation.org/our-work/activities/make-fashion-circular/report)

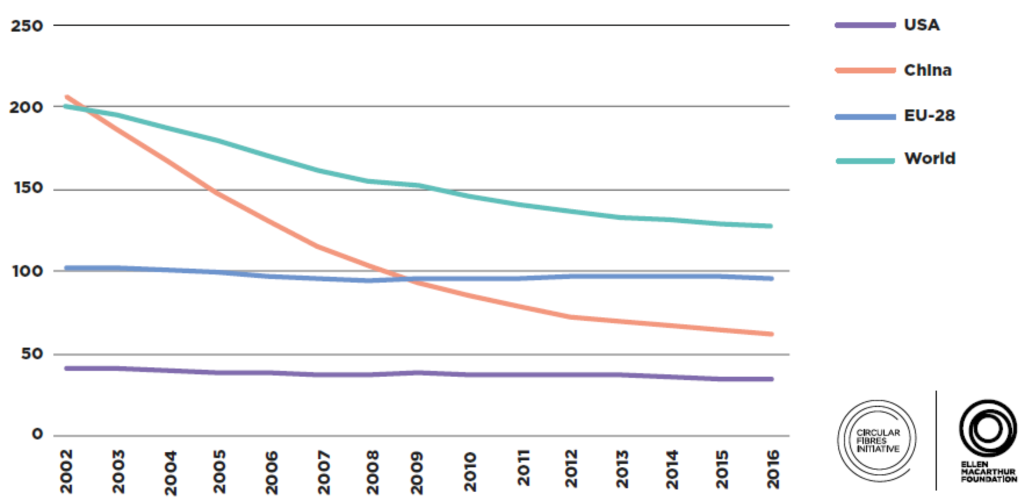


Figure 5.5 Clothing utilisation (including reuse within each region) of time (source : Ellen MacArthur Foundation, "A New Textiles Economy: Redesigning fashion's future", https://www.ellenmacarthurfoundation.org/our-work/activities/make-fashion-circular/report)

Of the Eionet countries only Sweden has specific targets for reuse of textile. This can also be seen from Eurostat trade data (Table 5.3), which show that there is a significant export of worn textiles.

Table 5.3 EU28 Extra trade (import and export), Eurostat, SITC product code 26901 (CLOTHING, CLOTHING ACCESSORIES, TRAVELLING-RUGS...)

Million tonnes	2014	2015	2016	2017	2018
Extra EU28 import	0,10	0,08	0,08	0,09	0,09
Extra EU28 export	1,22	1,29	1,30	1,39	1,47

Eurostat reports a generation of 2.18 million tonnes of textiles waste, of which 0,.6 million tonnes is generated by households as post-consumer waste. Furthermore, Eurostat reports waste treatment for 1.5 million tonnes of textile wastes, of which 1.22 million tonnes is being recycled. It is unclear how these amounts relate to the amounts of textiles waste generated.

Calculations indicate that 4.16 million tonnes of textiles end up in municipal solid waste[9] in the EU28. Following national MSW treatment strategies, textiles ending up in the residual waste are incinerated (34%) or landfilled (25%). The remaining 41 per cent is sent to a mechanical-biological treatment plant (MBT) to reduce the organic fraction prior to incineration or landfill (European Reference Model on Municipal Waste Generation and Management, 2018 version, 2015 data).

Mechanical recycling is the most common recycling process for textiles. In mechanical recycling processes, all substances, hazardous and non-hazardous, remain in the material and are carried over to the new product. Today, very little textile-to-textile recycling exists, mainly due to technical challenges with respect to fibre separation and fibre quality (Palm et al., 2014a). Moreover, fabric and fibre recycling are typically considered to be downcycling (at least in terms of fibre quality – in terms of other qualities of the end product, such as aesthetics, fit-for-purpose or material qualities defined by fabric construction rather than fibre quality, certain end products made from recycled fibres or fabrics may still be considered upcycling) (Sandin and Peters, 2018). Other major barriers, from a technical point of view, for high-quality textile recycling is the large mix of materials, coatings, dyes, and non-textile objects.

Mechanical fibre-to-fibre cotton recycling is currently only carried out for used textiles of 100% cotton. Mechanical recycling is not suitable for cotton mixed with other fibres, which constitutes a significant market share. In order to recycle the commonly used polycotton, a separate fractionation step is needed to separate the cotton from the PET. This may be done chemically by depolymerizing or dissolving one of the components while maintaining the other (Palme et al 2016).

To overcome the limitations and quality loss from mechanical recycling, some chemical recycling processes are under development, with the aim to achieve fibre-to-fibre recycling. Small-scale projects are ongoing, such as Eco Circle (Teijin), Worn Again and Re:newcell.

5.3 Environmental impacts and energy use

The production of textiles represents a significant proportion of the global environmental burden. It has been estimated that clothing is responsible for about 3 to 6.7 per cent of global human caused CO_2 emissions (Laitala, K. et al., 2018). Depending on the type of textiles produced also other impacts are generated such as water depletion and toxic pollution caused by the intensive use of pesticides (both mainly caused by the production of cotton). Also later stages in the production process give rise to even larger impacts. Wet treatment processes are major sources of toxic emissions, and spinning of yarns and weaving of fabrics often rely on the use of fossil energy.

[9] Calculations based on total amount of MSW and MSW composition data per EU28 member state

Figure 5.6 shows the potential contribution recycling and reuse of textiles could have. It is clear from the graph that avoided production of textiles represent a significant contribution.

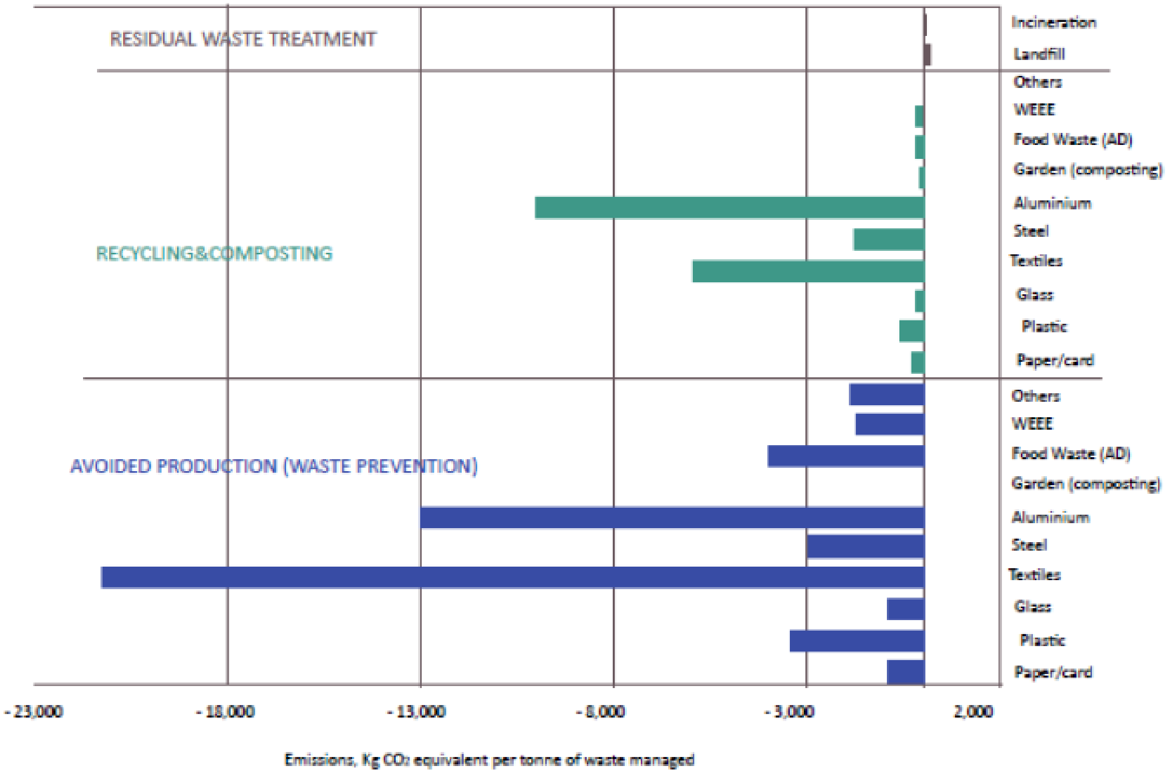


Figure 5.6 Indicative Climate Change Impacts of Key Waste Management Activities (excl. CO_2 from biogenic sources) (source: Hogg and Ballinger (2015) the potential of contribution of waste management ot alow carbon economy)

Own calculations based on IO modelling (done as part of ETC task 2.1.2.1 on Textile products and environment) indicate that CO_2 emissions related to the consumption of textiles by households in EEA-countries are round 18,3 kg CO_2-eq. per kg textile, which is in line with the numbers presented in the figure above.

The Nordic Council of Ministers' (2015) *Policy Brief: A Nordic strategy for collection, sorting, reuse and recycling of textiles* reports that an average kilogram of textiles has a carbon footprint of 15 kg and a 10,000 litre water footprint. The water footprint derives primarily from cotton production, much of which takes place in some of the world's most water-stressed areas.

6 Rubber

6.1 Overview

Natural rubber is a biotic material that is harvested mainly from rubber trees (*Hevea brasiliensis*) in the form of latex. Natural rubber consists mainly of polymers of the organic compound isoprene. Rubber trees grow in tropical forests close to the equator. Indonesia and Thailand are currently the biggest global producers and suppliers of natural rubber to the EU.

The global production of natural rubber was 13 million tonnes in 2016 (JRC, 2019). Natural rubber is mainly used in the production of tyres, which are responsible for about 75% of total EU rubber consumption (Figure 6.1). The other sector where natural rubber is used is the General Rubber Goods (GRG) applications. General Rubber Goods can be divided into three categories: industrial products, consumer products and latex products. Industrial rubber products include products used in machinery and household goods, e.g. moulded and extruded products, belting, hoses and tubes. Final consumer products where rubber is used are for example footwear, sports and leisure goods and toys. The third category of GRGs are latex products, such as dipped goods, adhesives, carpet underlay, gloves and condoms. (European Commission, 2017b)

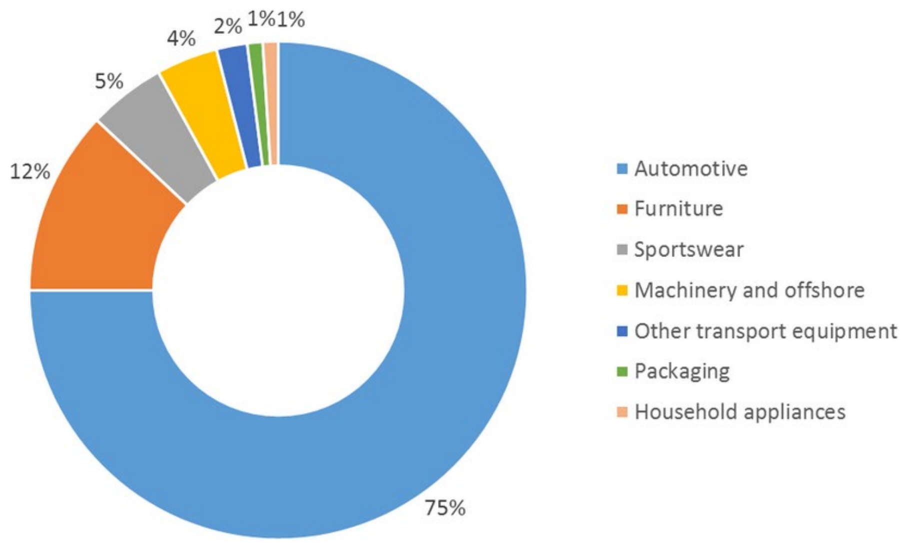


Figure 6.1 End uses of natural rubber, average figures for 2010-2014 (JRC, 2019).

Natural Rubber has been classified as a critical raw material on the 2017 list of Critical Raw Materials for the EU (European Commission, 2017a&b). The use of natural rubber in the EU is fully relying on import, since there is no domestic production of natural rubber in the EU. Also the refining (processing) of rubber is mainly done in the production countries. The economic importance indicator of natural rubber is 5.4 (2017) and the supply risk indicator 1.0 (2017) (Table 6.1). The supply risk indicator is influenced by the lack of readily available substitutes for all identified end-use applications of natural rubber and the low end-of life recycling input rate (EOL-RIR). (European Commission, 2017b)

Table 6.1 Natural rubber, key facts[10]*.*

Natural rubber	
Global production	13 million tonnes (2016)
Economic importance (EI)	5.4 (2017)
Supply risk (SR)	1.0 (2017)
End of life recycling input rate (EOL-RIR)	1 %

There are alternatives to natural rubber, such as synthetic rubber produced from petroleum, but the alternatives cannot match price and performance of natural rubber (European Commission 2017b). The global consumption of natural rubber is expected to continue to grow in the future (Ahrends et al. 2015).

6.2 Current management

Unlike many abiotic materials, the recovered biotic materials such as natural rubber often cannot be re-used in the same application or with the same properties as the original raw material due to contamination issues. The end-of-life recycling input rate of natural rubber is only 1% (European Commission, 2017b). Natural rubber is mostly recovered together with other materials and the closed-loop recycling of natural rubber back to the original application is not possible.

As indicated earlier, tyres are the main application of natural rubber in the EU. A car tyre contains on average 15 per cent of natural rubber and a truck tyre 30 per cent (JRC, 2019). In addition to natural rubber, tyres contain synthetic rubber, tire fillers such as carbon black and silica, steel cord and wires and chemicals, such as oils and zinc oxide. (European Commission, 2017b) Waste generated from end-of life tyres in EU was 3.36 million tonnes in 2016 (Eurostat, EU28, 16 01 03 end-of-life tyres). In Europe the management of end-of-life tyres is well organized. In 2016, 46 per cent of the end-of-life tyres was recovered for recycling, 27 per cent for energy recovery and 6% for backfilling (Eurostat).

Annually more than one million tonnes of end-of-life tyres are shredded into rubber granules that can be used in various applications such as synthetic turf, flooring for children playgrounds and sport surfaces, moulded objects, acoustic and insulation applications (European Commission, 2017b). Rubber powder derived from end-of-life tyres is used in rubber modified asphalt, which is durable and reduces tyre-pavement noise. The benefits of using rubber-modified asphalts are being more widely experienced and recognized, and the incorporation of tyres into asphalt is likely to increase. The whole of shredded end-of-life tyres is also widely used in civil engineering applications. Whole tyres are used in various civil engineering applications such as coastal protection, erosion barriers, slope stabilisation, road embankments, landfill construction operations, sound barriers and insulation. Tyre Derived Aggregate (TDA) made of shredded end-of-life tyres is used for example as lightweight fill in foundations for roads and railways and as a draining material replacement for sand and gravels. End-of-life tyres are also used as fuels (tyre-derived fuel TDF). (ETRM, 2015)

[10] *Economic Importance indicator (EI)* is calculated based on the importance of a given material in the EU end-use applications and performance of its substitutes in these applications. *Supply Risk indicator (SR)* is calculated based on factors that measure the risk of a disruption in supply of a specific material (e.g. global supply and EU sourcing countries mixes, import reliance, supplier countries' governance performance measured by the World Governance Indicator, trade restrictions and agreements, availability and criticality of substitutes). Criticality zone: SR ≥ 1 and EI ≥ 2.8. *EOL-RIR* is production of secondary material from post-consumer functional recycling (old scrap) sent to processing and manufacturing and replacing primary material input. (European Commission, 2017a)

The recycling of general rubber goods products (GRGs) mainly occurs for production scrap, but the recycling is limited due to the heterogeneity of elastomers used and the diversity of companies in the GRG sector making economies of scale difficult to get. Also contamination issues limit the recycling of GRGs. (European Commission, 2017b)

Even though end-of-life tyres can be recycled in various ways, it is important to highlight that tyre recycling is open-loop recycling, which means that recycled end-of-life tyres are mainly used in other applications than tires. The current recycling of end-of-life tyres and end-of-life GRGs are substituting other raw materials than natural rubber and therefore does not lead to a reduction of the natural rubber supply risk. (European Commission, 2017b)

6.3 Environmental aspects

The total area of rubber plantations in the world is estimated ca. 12 million hectares. However, the exact size of the area is uncertain and fluctuating. Rubber plantations compete with other crops (e.g. palm oil, grains) which limits the flexibility to expand the total acreage of natural rubber plantations. (JRC, 2019) Major increases in the production of natural rubber are not possible to be adjusted quickly because of the natural cycle of rubber trees. The immature period of a rubber tree is 5-7 years, after which the productive period is 20-40 years. (European Commission 2017b)

There are several environmental concerns that affect the production of natural rubber: the occurrence of natural disasters, scarcity of resources needed for production (e.g. water) and restrictions linked to the development of environmental regulations. (JRC, 2019) Also pest insects and pathogens can affect the supply of natural rubber. For example, the production of natural rubber in South American plantations is hindered by a fungal disease *Microcyclus ulei,* South American leaf blight that is able to destroy young rubber trees. Diseases affect the quality and quantity of rubber yield and create uncertainty about the supply of natural rubber in the coming years. (European Commission 2017b)

Rubber monoculture itself can have negative environmental impacts such as reduction in water reserves, reduced carbon stocks, negative impacts on soil productivity and biodiversity (Ahrends et al. 2015).

7 Conclusions

7.1 Summary of the losses

A summary of the estimated loss of the selected waste streams studied is compiled in Table 7.1. The table only includes information on waste streams lost because they are landfilled or incinerated, but the ones that are downcycled.

Table 7.1 Quantification of losses in Europe based on published data.

Stream	Amount generated (EU 28)	Loss (landfilled, incinerated)	Main causes for losses
Batteries	1.9 Mt waste batteries generated of which majority is lead acid batteries (Eurostat 2016)	40 kt landfilled (Eurostat 2016). 128 kt of portable batteries does not end up in collection and 35 kt is estimated to end up in municipal waste (Stahl et al, 2018).	Consumer awareness and inadequate collection: portable batteries end up in mixed waste, stocks at home, or lost through WEEE.
WEEE	10.3 Mt of WEEE was generated in 2015 (Huisman et al. 2015)	63 % of WEEE (ca. 6,5 Mt) does not end up in collection. 75 kt estimated to end up in municipal waste. (Huisman et al. 2015)	Consumer awareness: Stocks at home and misplaced waste fractions Inadequate collection
Plastic waste			
- plastic packaging waste	16.3 Mt (Eurostat 2016)	over 9 Mt (Eurostat 2016)	Inadequate collection systems resulting in poor quality & the low price of virgin materials and costs for sorting and processing including investment costs cause that the products from secondary plastics are typically used in low value applications
- plastic waste from construction	- 1.0 Mt (Eurostat 2016) - 1.5 Mt (Plastics Europe 2017a)	over 1 Mt (Europe Plastics 2017c)	Challenges in identification and separation of various plastic products in buildings
- plastic waste from end-of-vehicle	- 1.2 Mt (NewInnoNet 2016)	only data for shredder waste published: 0,5 Mt (Eurostat)	Technical challenges to recover recyclable plastics from end-of-life vehicles & recycling governed by metal recovery.
- plastic waste from WEEE	2.4 Mt (Huisman et al. 2017)	no data	Recycling governed by metal recovery.

Stream	Amount generated (EU 28)	Loss (landfilled, incinerated)	Main causes for losses
Textile	5.6 Mt (Friends of the Earth, 2013)	4.64 Mt (calculated, 80 % loss) 4.16 Mt (calculated waste model	Only small amount separately collected. Mixed fibres are difficult to recycle.
Rubber	Waste generated from end-of life tyres was 3.36 Mt in 2016 (Eurostat)	10 kt of end-of-life tyres landfilled and 110 kt incinerated (Eurostat, 2016)	In most applications, natural rubber is mixed with other materials and separate recovery of natural rubber is not possible. Contamination issues

7.2 Reasons for losses

In previous chapters, various challenges or reasons causing losses have been identified. Poor or inadequate collection is a great challenge that is linked to almost all of the analysed waste streams. Awareness of consumers is another important factor in increasing the collection rates of different waste fractions. There are also various challenges related to the quality of the waste materials, such as materials heterogeneity and content of hazardous substances that hamper recycling. For some of the materials, technological challenges are also important reasons for losses, as well as lack of market or demand for recyclables. The reasons for material losses are often cross-linked, for example waste quality (heterogeneity) and lack of cost efficient technology. Challenges and reasons causing losses that were identified in this report are listed in Table 7.2.

Table 7.2 Challenges or reasons causing losses.

Challenge	Specification	Waste types	Description of loss - examples (e.g. value, “downcycling”) for certain streams
Awareness	Misplaced waste fractions Stocks at home	Plastics Electronics Portable batteries Textiles	750 kt of WEEE end up in waste bin with MSW (Huisman et al. 2015) 35 kt of portable batteries end up in municipal waste (Stahl et al, 2018) > 4 Mt of textiles ends up in residual waste
Collection	Poor collection systems Packs made from multi-materials or covered by sleeves might end up in the wrong material fraction Batteries embedded in electronic appliances not removable by consumers	Plastics Electronics Textiles Batteries	Collection of plastic packages currently 43 % (data for 2016, Eurostat) Especially mechanical or chemical recycling of PVC would create environmental benefit

Challenge	Specification	Waste types	Description of loss - examples (e.g. value, "downcycling") for certain streams
Export of waste	Lower processing costs	Plastic waste Electronics Textiles	1.5 Mt of WEEE is exported out of EU (Huisman et al. 2015) Nearly half of the plastic packaging waste has been exported outside Europe, in 2015 mainly to China and lately to other countries in Asia. (Commission, 2018) 1.5 Mt of worn textiles are exported outside of EU
Complementary recycling	(Unofficial) recycling or reuse that is not reported	Electronics Textiles	0,95 Mt of WEEE recycled under non-compliant conditions in Europe (Huisman et al. 2015) Reuse of textiles through the 'informal' sector (donation between family and friends) or through second hand shops is not included in the waste statistics.
Scavenging of valuable parts	Scavenging of valuable parts and components	Electronics	750 kt of WEEE scavenged for valuable parts (Huisman et al 2015)
Sorting	Similar physical properties of materials to be separated Black packaging cannot be sorted by plastic type	Plastic packaging	Depending on throughput: purities not better than 80-95 % by mechanical sorting
Complexity of waste	Different types of materials or fractions glued or put together	Multimaterial packages Electronics Textiles	A high share of plastics products used in construction and in automobile sector cannot be recycled because not possible to separate the streams Textiles containing different types of fibre a difficult to recycle
Technological challenges	Lack of proven technology Different technologies for recovery of metals (choice of metals for recovery	Lithium recycling from li ion batteries, rare earth elements from NiMH batteries	

Challenge	Specification	Waste types	Description of loss - examples (e.g. value, "downcycling") for certain streams
	process, metals lost in rejects/slags)	Recovery of natural rubber Polystyrene packaging Recovery of several CRMs from WEEE	
Content of hazardous/unsuitable substances	Additives added in processing of virgin materials	Plastics (packaging) Soft PVC (DEPH plasticizers) Electronics Textiles Rubber	Flame retardants in most WEEE (with exception for a few products) Chemicals used during the production of textiles remain in the textiles when reused or recycled (mechanically)
Availability and price of virgin material	Costs for processing high compared to price for virgin materials	Plastic wastes Lithium in LIBs	
Downcycling	Recycled in lower value applications	Plastics Textiles Natural rubber	
"Not real recycling"	Low content of recyclables in products		Share of recyclables in plastics generally low
Lacking design for recycling	Poor separability, poor traceability of materials for recycling	All streams	without fundamental redesign and innovation, for example, only about 30 % of plastic packaging will never be reused or recycled
Environmental impacts of recycling process	Use of chemicals in processing, high energy need	Chemical recycling of textile waste Chemical treatment of plastic waste? Metal recovery from WEEE Metal recovery from LIBs	
Material identification (identification of recyclable stream)	Great variety of composition	Plastics Textiles	
Traceability in value chain	Lack of confidence in quality		
Market issues (limited market for several polymers)	Secondary sector characterised by many small actors who are vulnerable to market shocks.	Typical for plastics	

Challenge	Specification	Waste types	Description of loss - examples (e.g. value, “downcycling”) for certain streams
	Primary producers are 10 times bigger Global plastics markets have historically been concentrated in a small number of countries Effects of China import restrictions illustrate the risks of market concentration		
Regulatory burden	Permitting requirement for waste Image of product if based on waste (can also be a benefit)	Plastics end-of-waste concept not European wide (lack of clear rules) e.g. For plastics	
Statistics of streams/treatment	Use as indicators in EU	Plastics waste: lack of common calculation methodology to calculate EU recycling targets, including more measuring points (collection, sorting & recycling) to efficiently measure the material flow Batteries other than lead-acid and ni-cd defined as “other batteries” and reported together Textiles : limited reliable data available Natural rubber: Only used tires are reported as rubber waste	“reliability” of calculations

7.3 Consequences of the losses and linkages to circular economy

Eurostat data gives important information on waste amounts generated and treated in Europe which can be used as indicators for following the waste management development in different member states and also forms the base for policy actions. The information from waste streams with very different characteristics is agglomerated, which means that detailed information on specific streams and its treatment is not available. The Eurostat data indicate clear losses on all selected streams reported here. However, for analysis of data and linking the data to circular economy actions, complementary information on single streams need to be collected, for example from the RMIS database.

For some waste streams reported in Eurostat, further clarification on data included is required. For example, in this report textile data reported by Eurostat has been compared to data collected in other EEA task for municipal solid data, and the comparison indicates a significant difference between reported amounts of collected textiles. Own calculations indicate that 4.16 million tonnes of textiles are present in MSW (from households only) sent for final treatment (representing an actual loss for reuse or recycling). Furthermore, Eurostat reports that 1.5 million tonnes of selective collected textile waste (both industry and households) is treated within the EU28. 1.2 million tonnes hereof is being recycled within the EU28, the remaining 0.3 is sent to disposal or incineration with energy recovery (representing a loss for reuse or recycling). Moreover, there is a discrepancy between exported amounts of 'worn textiles' and the amounts of waste textiles not treated within the EU28. This might be due to the fact that the separate collection of given fractions of textiles are not included in the waste statistics.

Inadequate collection is the main reason for resource losses for most of the waste streams. Therefore, in order to reduce losses, special measures are needed to improve the separate collection of batteries, WEEE, waste plastics and textiles. The collection rates of certain materials vary significantly between EU countries. For example, if the countries with lowest collection rates of WEEE could raise their collection rates in line with the current EU average, it would add more than 50 kilotonnes of WEEE collected per year. Furthermore, studies indicate that up to 50 per cent of plastic packaging waste is often misplaced in household waste and therefore not directed to material recycling. It has been roughly estimated that around half of plastic packaging generated in Europe could be recycled economically and environmentally effectively. More efforts are needed in introducing efficient systems for collection and sorting of plastic wastes. In addition to improvements in the collection infrastructure of different waste streams, it is important to raise the awareness of consumers in order to achieve higher collection rates.

The wastes in focus in this report are often downcycled and seldom recycled into the same application. Thus technological solutions are needed in order to produce higher quality secondary materials. For example, in the case of plastics, separately collected single polymer plastics can be mechanically recycled. However, mechanical recycling is not enough for heterogeneous plastic waste streams containing, for example, multi-material packaging and various additives and contaminants. Chemical recycling is an option for plastics not suitable for mechanical recycling, but more cost efficient methods are still needed.

Complexity of waste materials, miniaturization of products and containing of hazardous substances are reasons hampering the recycling of certain waste streams. To achieve product reuse or high quality recycling targets and closed loops, the products must be designed for reuse or recycling in the future. When it comes to electronics, there is also a need to tackle the obsolescence phenomenon in order to prolong the service life of products. The strategies against obsolescence must aim at achieving an assured minimum lifetime and an extension of product lifetime, and also affect consumer behaviour in order to extend the service life of products (Oehme et al. 2017). For plastics, actions include design of recyclable plastic products, limitations for the production of single-use plastic products and prolongation of the life span of plastic products (e.g. by introducing refillable packaging). A European Strategy for Plastics in a Circular Economy (European Commission 2018) sets the target that by 2030 all plastics packaging placed on the EU market is either reusable or can be recycled in a cost-effective manner.

Poor collection and recycling of batteries and WEEE also causes losses of critical raw materials. Critical raw materials, which are of high economic importance to European economy and possess high risk of supply, are used in various types of batteries and EEE. By enhancing the recycling of these critical raw materials from batteries and WEEE, their supply risk can be reduced. For example it has been estimated that the potential amount of secondary cobalt from the LIBs of end-of-life EV's is rapidly growing in the forthcoming years, and by 2030 recycling of EV batteries could provide for approximately 10 per cent of the European cobalt consumption in the EVs sector (Alves Diaz et al., 2018). The production of secondary raw materials typically causes lower environmental impacts when compared to the production of the primary raw materials. Therefore, reducing resource losses and increasing the recycling rates of CRMs could also have a positive environmental impact and reduced GHG emissions.

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9 List of abbreviations

BEV	Battery electric vehicle
EEE	Electrical and electronic equipment
EI	Economic importance
EOL-RIR	End of life recycling input rate
EV	Electric vehicle
CRM	Critical Raw Material
GRG	General Rubber Goods
HDPE	High density polyethylene
Kt	Kilotonnes
LDPE	Low density polyethylene
LIB	Lithium-ion battery
MSW	Municipal solid waste
Mt	Million tonnes
NACE	Statistical classification of economic activities in the European Community
NiMH	Nickel-metal-hydride
PE	Polyethylene
PET	Polyethylene terephthalate
PHEV	Plug-in hybrid electric vehicle
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl chloride
REE	Rare earth elements
RMIS	Raw Material Information System
SDA	Small device applications
SR	Supply risk
TDA	Tyre Derived Aggregate
TDF	Tyre Derived Fuel
WEEE	Waste electrical and electronic equipment

European Topic Centre on Waste and Materials
in a Green Economy
Boeretang 200
BE-2400 Mol
Tel.: +14 33 59 83
Web: wmge.eionet.europa.eu
Email: etcwmge@vito.be