Tampere University

Valeria Poliakova

DEMONSTRATION OF WASTE STATUS TERMINATION FOR PLASTICS

Faculty of Engineering Sciences
Master's Thesis
January 2019

ABSTRACT

Valeria Poliakova: Demonstration of waste status termination for plastics
Master's thesis
Tampere University
Materials Science and Engineering
January 2019

Global pollution of land and ocean associated with unmanaged plastic waste is one of the drivers behind emerging of the circular economy. Recovered plastic waste serving as a raw material can be circulated in the industrial system, generating economic, social and environmental benefits.

Recovery of the waste results in the waste serving a useful function. At some stage during recovery process, the waste can be shown to achieve sufficient properties to be used for a certain application in a safe for health and environment manner. That stage of the process is a point of recovery. Termination of a waste status of a material requires from the manufacturer of that material documented demonstration that the produced material is safe for health and environment, has an existing market, fulfills technical requirements for an application and meets product regulations and standards.

In absence of EU-wide or Finnish national methodology for assessment of material status of the plastic waste, the author reviewed technical guidelines, standards and scientific articles for establishing the criteria for the assessment. Waste and chemical regulations, products standards and industrial reports were used for providing the background information for the assessment. Material statuses of PE pellets, produced in Finland from post-consumer industrial/commercial and construction and demolition wastes, were assessed. The author suggested that only waste status of pellets produced in Finland from transparent packaging could be terminated. The detailed assessment and list of documentation used are presented in the work.

Termination of the waste status was demonstrated through evaluation of the information collected about recyclate against criteria developed during preparation stage of the work and documentation of the whole process.

The main expected benefit of the material status assessment and terminated waste status is increased level of knowledge about the properties of the recovered material resulted in increased demand for the recyclate and its widespread recirculation in industrial system.

Keywords: recycling, EoW methodology, polyolefins, Finland

The originality of this thesis has been checked using the Turnitin Originality Check service.

PREFACE

This Master's Thesis was written during the final stage of RECOMPOSE project, which was launched as part of BioNets program in 2017. The program goal was to generate new business ecosystems, projects and business development platforms for Finland's bio and circular economy. The work performed was a part of parallel to a public RECOMPOSE project, undertaken by Borealis Polymers Oy.

"One man's waste is another man's raw material" – a phrase so often quoted nowadays, has shown to be rather simplified, when applied to real industrial processes functioning according to legislation. This 81-page long work explains the details behind termination of waste status.

I would like to express my gratitude to my two supervisors, Auli Nummila-Pakarinen and Essi Sarlin for their time, effort and experience shared. I have learned a great deal about the subject thanks to their detailed feedback and guidance during the writing process. I would also like to express my great appreciation to Pekka Kortesmaa and Jani Salminen for their comments and encouragement during the work. I am grateful for the enthusiastic and motivating attitude and information provided to Mikko Ronkanen. My special thanks are extended to all my work colleagues and in particular to the laboratory staff of Borealis Polymers Oy for their practical help with experiments and knowledge shared. Finally, I'm thankful to my family for their listening and encouraging on the way.

Helsinki, 13 January 2019

Valeria Poliakova

CONTENTS

LIST OF TERMS AND ABBREVIATIONS

A	**Additives –** all the constituents, which are intentionally added to stabilize the substance and only for this purpose (ECHA, 2017). For other possible constituents of plastic such as pigments, reinforcing supplements, processing aids, etc., the term "**property-modifiers"** is used.
	Article is **"**an object which during production is given a special shape, surface or design, which determines its function to a greater degree than does its chemical composition" (EPC, 2006).
B	**B&C** is Building and Construction.
	Batch is a quantity of material regarded as a single unit and having a unique reference (CEN/TR 15353, 2007) or "quantity of PE recyclate that has homogeneous characteristics within the specified tolerances" (SFS-EN 15344, 2007).
	Bio-waste is "biodegradable garden and park waste, food and kitchen waste from households, restaurants and retail premises and comparable waste from food processing plants" (EPC, 2008).
	By-product is non-waste resulting from a production process and satisfying by-product criteria outlined in Article 5 of Directive 2008/98/EC (see section 2.6 for details).
C	**C&D** is Construction and Demolition.
	Challenge test is test of a recycling process in which purposely specified contaminants or damaged materials are introduced in prescribed quantities to judge the ability of the recycling process to produce material with certain specified properties (SFS-EN 15343, 2007).
	Construction and Demolition waste - see section 2.3 for details.
	Contaminant – unwanted substance or material (preferred term over **impurity**) (CEN/TR 15353, 2007).
D	**Disposal** is any (waste treatment) operation that is not recovery (EPC, 2008).
	Downstream user is a European Economic Area based industrial/professional user that is blending substances into new formulations to be placed on the market or using them for producing articles (ECHA, continiously updated).
E	**EEE** is Electrical and Electronic Equipment - "equipment which is dependent on electric currents or electromagnetic fields in order to work properly and equipment for the generation, transfer and measurement of such currents and fields […]", see Directive 2012/19/EU on Waste Electrical and Electronic Equipment (WEEE) for full definition.
	ELVs are End-of-Life Vehicles.
	End-of-Waste criteria - specifications that a candidate waste stream must fulfil in order to leave the waste domain (Villanueva, et al., 2010). In newest amendment to WFD the "certain type of waste" rather than "waste stream" has to fulfil the criteria.
	EoW is End-of-Waste.
	EoW material producer - the person who first transfers the material to another person as non-waste (European Comission, 2012).
	EPR - Extended Producer Responsibility scheme means a set of measures that Member State is taking to ensure that producer bear the financial and organizational (in some cases only financial) "responsibility for the management of the waste stage of a product's life cycle" (EPC, 2018).
	EWC-Stat is statistical waste nomenclature.
F	**FT-IR –is Fourier-Transform Infrared Spectroscopy.**
	Flake – form of material, resulting from shredding (see section 3.3 for details).
	Food contact material - all materials and articles intended to come into contact with food (ESFA, 2015).

H **Hazardous waste** is “waste that displays one or more of the hazardous properties listed in Annex III” of WFD (EPC, 2008).

HDT is Heat Deflection Temperature.

Home electric and electronic appliances is electric and electronic appliance used at home as well as similar in quality and amounts appliances used in commerce, industry and other activities (FINLEX, 2011).

I **Industrial symbiosis -** synergistic exchange of waste, by-products, water and energy between individual companies in a locality, region or even in a virtual community (Debergh, et al., 2015).

L **LoW** – List of Waste, common encoding of the waste classes used in EU (European Comission, 2000).

M **Material** can refer to any substances or object, both virgin and waste-originated (Kauppila, et al., 2018).

Mechanical recycling - see section 3.2.

MFR is Melt Flow Rate.

Mixed MSW is MSW excluding separately collected fractions.

Mixture “a mixture or solution composed of two or more substances” (EPC, 2006).

Monomer - “a substance which is capable of forming covalent bonds with a sequence of additional like or unlike molecules under the conditions of the relevant polymer-forming reaction used for the particular process” (EPC, 2006).

MSW is Municipal Solid Waste.

Municipal waste - see section 2.3.

O **OIT** is Oxidation Induction Time.

P **Packaging** is “all products made of any materials of any nature to be used for the containment, protection, handling, delivery and presentation of goods, from raw materials to processed goods, from the producer to the user or the consumer”. See Directive 94/62/EC on packaging and packaging waste for full definition.

PE-HD is High-Density Polyethylene.

PE-LD is Low-Density Polyethylene.

PE-LLD is Linear Low-Density Polyethylene.

Placing on market “of a substance or mixture means making it physically available to third parties, whether in return for payment or free of charge” (ECHA, continiously updated).

PO is Polyolefin.

Polymer molecule is “a molecule that contains a sequence of at least 3 monomer units, which are covalently bound to at least one other monomer unit or other reactant” (ECHA, 2012).

Polymer is a substance meeting the following criteria (ECHA, 2012):

- > 50 % of the weight of that substance consist of polymer molecules
- The amount of polymer molecules presenting the same molecular weight must be less than 50 weight percent of the substance.

Post-consumer waste is waste “generated by households or by commercial, industrial and institutional facilities in their role as end-users of the product which can no longer be used for its intended purpose” (ISO 14021:2016, 2016).

Post-industrial waste is waste generated during converting or manufacturing processes (BIO, 2011), also referred to as **pre-consumer waste**.

PP is Polypropylene.

PPWD is Packaging and Packaging Waste Directive.

Primary raw material is a “material which has never been processed into any form of end use product” (SFS-EN 13430, 2004).

R **Raw material** is a “basic substance or mixture of substances in an untreated status which either enters a production process or is consumed directly” (Eurostat, 2015).

Recovery is any operation, which results in waste becoming useful, i.e. replacing materials serving a specific function, or preparation of waste to fulfill this function in the industrial or wider economy context (EPC, 2008).

Recycling see section 3.2.

Reprocessing see section 3.2.

S

Substance - “a chemical element and its compounds in the natural state or obtained by any manufacturing process, including any additive necessary to preserve its stability and any impurity deriving from the process used, but excluding any solvent which may be separated without affecting the stability of the substance or changing its composition” (EPC, 2006).

V

Virgin material – previously unused raw material.
(Oxford Reference, 2017).

VOC is Volatile Organic Compound.

W

Waste is “any substance or object, which holder discards or intends or is required to discard” (EPC, 2008).

Waste holder is “the waste producer or the natural or legal person who is in procession of the waste” (EPC, 2008).

Waste treatment is recovery or disposal or preparation for them (EPC, 2008).

WEEE is Waste Electric and Electronic equipment.

WFD is Waste Framework Directive.

WstatR refers to Waste Statistics Regulation.

.

1. INTRODUCTION

More than half of ever produced plastics were produced during 2000-2015 (OECD, 2018)

"The long-term goal is for the EU to become a recycling society that seeks to avoid waste and uses waste as a resource" (European Comission, 2005)

Unmanaged waste is an economic, environmental and social problem. It is estimated that in 2010, 4.8-12.7 million metric tons (Mt) entered the ocean as a result of mismanaged plastic waste in 192 coastal countries and amount was estimated to increase tenfold by 2020 (Jambeck, et al., 2015). For comparison, in 2016 in EU around 60 Mt of plastics were produced. Additionally to marine pollution and economic loss (Ellen MacArthur foundation, 2016), unmanaged plastic waste results in increase of concerns of consumers about the effects of plastic, plastic packaging and plastic waste on environment (Ipsos Mori, 2018) and even intentions to ban some single-use plastic products (European Comission, 2018).

However, modern life without plastic is utopia. There are number of applications, where use of plastics material is highly justified. Explicitly different from other materials' properties allow plastics to be used for protection and preservation of foodstuffs, for fuel economy in vehicles, for durable and impermeable infrastructures and for applications, where use of biomass-derived materials would result in biodiversity loss (OECD, 2018). Packaging is the single biggest application of plastics (APM, 2017) and extensive plastic use in packaging is not accidental.

Packaging purposes are to contain, protect and preserve the product. It also increases convenient use of a product, provides mean for identification of the content and is used as a marketing instrument (Emblem, 2012). Plastics are widely used as packaging material due to their light weigh, chemical resistance, barrier properties, sealing properties and transparency (Delgado, et al., 2007). Use of plastics packaging makes our life more convenient, but also substantially safer and resource efficient. Plastic packaging protects medical instruments against contamination, reduces weight of transported goods and therefore helps to decrease emission and energy used for transportation and prevents food waste by allowing contamination free and controlled atmosphere inside the package (APM, 2018).

Harvesting of plastic material potential and avoiding problems associated with unmanaged plastic waste is attainable with sound plastic waste management. Among the main principles guiding the waste management in Europe and Finland, are waste hierarchy, polluter-pays principle and extended producer responsibility principle (Laaksonen, et al., 2017).

Waste hierarchy means that waste prevention and management actions are placed in priority order, in which prevention of waste is the first option (EPC, 2008). Waste is prevented, for example when plastic packaging manufacturers work on the package design to minimize the amount of materials used. Cleaning and reparation, i.e. preparation for re-use, is the second option in waste hierarchy. Re-use of plastic crates, boxes and wooden pallets is common practice in Finland, resulting in only 40% of used packaging eventually becoming available for recycling and energy recovery (Rinki, 2018), which are the next options in waste hierarchy. Safe disposal of the waste, for example at properly organized landfill, is the last option.

Finnish waste management system was recently affected by limitation to deposit organic waste to landfills originated from Government Decree on waste (FINLEX, 2013). According to that limitation, the waste with content of organic carbon higher than 10% cannot be placed to the landfill. After the limitation is fully in force in 2020[1], no plastic waste can be placed to the landfill

[1] The limitation is active from 1.1.2016, but for waste separated from construction and demolition waste – only from 1.1.2020.

(Järvelä & Järvelä, 2015). This limitation resulted in development of waste treatment facilities and increase in local energy recovery capacity (Laaksonen, et al., 2017).

In the recent waste legislation transformation of waste management into sustainable material management is emphasized. Such transformation is linked to social, economic and environmental benefits such as preservation of environment and human health, efficient use of natural resources and reducing the dependence of the EU on imported resources (EPC, 2018). Use of waste as raw material is not a new idea, but practical industrial scale implementation of it is not as straightforward, as one can imagine.

Physical transformation of waste into material can be achieved by material recovery, recycling. In the literature reviewed, at least three types of recycling were mentioned with respect to plastics:

- Biological, where microorganisms are used in the controlled treatment of biodegradable plastics to produce organic residues and water together with carbon dioxide (composting) or with methane (digestion) (CEN/TR 15353, 2007).
- Chemical (feedstock), where chemical structure of plastic waste is changed through cracking, gasification or depolymerization and new raw materials are produced. Energy recovery or incineration are not considered chemical recycling (CEN/TR 15353, 2007).
- Mechanical, where no significant change of chemical structure is taking place and plastic waste is processed into secondary raw materials or products by shredding and melting (CEN/TR 15353, 2007; Villanueva & Eder, 2014).

Recovered material, however, does not automatically become a new raw material, but its waste status should be terminated. Termination of waste property is done through demonstrating compliance with End-of-Waste (EoW) conditions. EoW concept can be compared to a filter that allows the waste material that is shown to be good and safe back into manufacturing system and keeps waste, which can cause harm for human and environment, away from it. By diverting part of the waste material away from disposal, the filter is one of the tools of creating the circular pattern of the stream (see figure 1 for author’s visualization of the concept).

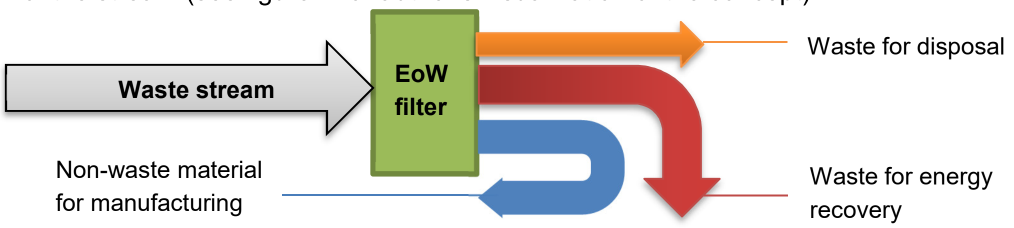

Figure 1. *Visualization of the EoW concept*

The question presented to the writer of the present work was “**How termination of waste status of polyolefins in Finland can be demonstrated?**”

In order to answer that question, the author examined regulations, standards, scientific and professional articles and web sites of companies and authorities with the following objectives:

- to determine, what “waste status” means and how waste plastic differs from non-waste
- to explore, what are the conditions for termination of waste status
- to present background information, necessary for evaluation of compliance of waste polyolefins with these conditions
- to find methods to demonstrate the compliance with these conditions

To test the ideas collected during the work, two Finnish waste sub-streams, namely industrial/commercial flexible plastic packaging and waste plastic pipes - were chosen as test streams. Materials status assessments and an example of documentation of such assessments are presented in Chapter 6.

The scope of the work in hand is defined by the following aspects:

1. The work is limited to plastic waste. Packaging waste is the main source of plastic waste in Europe (Plastics Europe 2017) and in Finland (Sahimaa & Dahlbo, 2017). Other con-

siderable sources are building and construction waste, waste electronic, electrical equipment, end-of-life vehicles (Hopewell, et al., 2009) and agricultural waste (Villanueva, et al., 2010).
2. The research is focused on polyolefins polyethylene and polypropylene. They constitute almost half of the EU demand for plastics (APM, 2017) and are estimated to be the most abundant polymer type in plastic waste (Delgado, et al., 2007).
3. The end of waste status termination is demonstrated after mechanical recycling of plastic waste
4. As material should first become waste to become non-waste, other than waste materials (such as by-products) are explained in the text but excluded from the review.
5. While documentation related to shipment of the waste is a relevant source of information for the purposes of the work, examination of such documentation is excluded from literature review due to time constrains

2. SEGMENTATION OF PLASTIC WASTE

Waste is “any substance or object which the holder discards or intends or is required to discard” (EPC, 2008), as defined by main piece of waste legislation – Waste Framework Directive (WFD).

Waste can be divided into waste categories – grouping of waste based on common characteristics. Division is often country-specific. Residual waste, industrial waste, commercial and institutional waste, construction and demolition waste are examples of the categories that can be found in general use and academic literature (Lagerkvist, et al., 2010; Dixon, et al., 2010). On the other hand, municipal waste, hazardous waste and variety of waste-related abbreviations such as WEEE, ELV and PPW can be encountered by the reader (EPC, 2008; EPC, 2011; EPC, 1994).

The chapter 2 provides readers with definitions related to plastic waste, describes a spectrum of ways the waste stream is divided in sub-streams, defines which sub-division is formal and which is not and describes the sources, where the information regarding to sub-streams can be found. As was stated in one of the European Commission guidelines, precise definitions are important, at least because legislation refers to them (European Comission, 2012).

2.1. Informal waste classes

In the book Solid Waste Technology and Management edited by T. Christensen, solid waste is divided into few classes. Despite many references to these classes of waste in literature, the division presented below is not EU wide.

The first class described by Christensen is residential waste**,** where household waste, garden waste, bulky waste and household hazardous waste belong. Household waste is waste produced from everyday activities and includes packaging, kitchen waste, broken toys, household appliances and old clothes, to mention some examples. Bulky waste contains for example furniture and big household appliances. Residential waste is defined differently in different countries, what complicates the cross-country comparison, but on average around 500 kg/person/year is generated in Europe. Plastics are reported to constitute around 11% of household waste. (Christensen, et al., 2010)

The second class is commercial and institutional waste. The sources listed for these wastes are “retail stores, hotels, restaurants, health care (except for hazardous healthcare waste), banks, insurance companies, education, retirement homes, public services and transport”. Only part of that waste is usually handled within municipal waste system. Plastic wastes are indicated to constitute 10-12% of commercial and institutional waste. Packaging waste is an important part of these waste and enterprises producing high volumes of clean plastic (and other) packaging waste might have their own collecting and sorting facilities for later selling that waste within secondary raw material sector. (Christensen & Fruergaard, 2010)

The waste generated by industrial production and manufacturing constitutes the third class, industrial waste**.** Information available on that type of waste is often limited in many EU countries to part of industrial waste handled within municipal waste system and to public industrial reports. Part of the industrial waste can be in periods traded as secondary raw materials. Plastic wastes can be potentially generated as a part of number of industrial processes, such as manufacturing and preparation of chemicals and related products; manufacturing of furniture, machinery, electronic and electrical components and equipment, transportation equipment, measuring, analyzing and controlling equipment; and manufacturing of miscellaneous plastic products such as toys, sport and athletic goods. (Christensen, 2010)

The last class described by Christensen et al. is Construction and Demolition waste (C&D). It is waste generated during building, repair or remodeling, or removal of constructions, which could be roads, residential or non-residential buildings. Traditionally, it has been landfilled. It has been documented that about 90% of this waste can be easily recycled. C&D waste can be divided into three subcategories: buildings, roads and excavations. Data for Denmark for 1990 indicates, that demolition generates 1625-1760 kg/m^2 (of building) of waste (undetectable amount of plastic generated), remodeling - 50 kg/m^2 (waste plastic < 0.5 kg/m^2) and construction - 23 kg/m^2 (waste plastic 1 kg/m^2). Pipes, gutters, electrical installations, ceilings, decorations, windows, panels, cabling and flooring are examples of plastic wastes found in building wastes. Pipes and drains are also part of road and pavement construction. (Christensen, 2010) Plastics are reported to constitute 0.1 – 2% of C&D waste (Gálvez-Martos, et al., 2018).

2.2. Post-industrial and post-consumer waste

In literature, plastic waste, as well as other wastes, is often divided into post-industrial or pre-consumer waste and post-consumer waste (Mehmood, et al., 2010; BIO, 2011; Ragaert, et al., 2017)

Post-industrial waste or pre-consumer waste or industrial scrap is “waste generated during converting or manufacturing processes” (BIO, 2011). It would be usually described as clean, with known composition and often constituted by homogeneous waste stream (Ragaert, et al., 2017). The examples of post-industrial plastic waste would be trimmings and cutting generated in the process, injection molding runners, waste from products changeover or defective products (Ragaert, et al., 2017; Järvinen & Saarinen, 2016). It can be classified as waste by some authorities and as non-waste by others (Villanueva & Eder, 2014). Standard ISO 14021 defines pre-consumer material as the “material diverted from the waste stream during a manufacturing process” but explains, that such material as rework, scrap and regrind, which is generated during the process and which can be absorbed back in the process should be excluded from definition of pre-consumer material (see also *internal waste* in sub-chapter 2.6) (ISO 14021:2016, 2016).

Technical report by Debergh et al. approaches the pre-consumer waste from industrial symbiosis point of view. They divide the total flow of plastic waste into industrial processing waste and post-consumer waste. Industrial processing waste is constituted of substances rather than of articles and is often directly exchanged, without recycling. Three industrial symbiosis types can be distinguished, namely symbiosis within a company, between companies on a bilateral basis or through some type of market interaction (Debergh, et al., 2015). Industrial processing waste is generally circulated inside the industry by being reused in industrial process or being sold to reprocessors without entering the usual waste management system (BIO, 2011; Debergh, et al., 2015). Data on industrial processing waste is often not directly available and the stream is “considered outside of the boundaries of common definition of recycling” (BIO, 2011).

ISO 14021 standard defines post-consumer material as “generated by households or by commercial, industrial and institutional facilities in their role as end-users of the product which can no longer be used for its intended purpose” (ISO 14021:2016, 2016).

Sources of post-consumer plastics wastes mentioned by researchers (Villanueva & Eder, 2014; Van Eygen, et al., 2018; Hu, et al., 2013) are Municipal Solid Waste (MSW) or plastic packaging from MSW, Construction and Demolition (C&D) waste, Waste Electric and Electronic Equipment (WEEE) and End-of-Life Vehicles (ELV) or automotive shredder residues (Hu, et al., 2013) and agricultural waste (Villanueva & Eder, 2014).

2.3. Waste types in waste legislation

Directive 2008/98/EC (EPC, 2008) also known as Waste Framework Directive (WFD) is the main document, where terminology related to waste is defined, waste management hierarchy outlined and conditions to classify waste as hazardous are described in Annex III. Recent Directive (EU) 2018/851 clarifies many concepts defined in WFD. It is the newest amendment to the WFD published on 14.6.2018.

Officially, the basis for the waste classification is European List of Waste (LoW) by Commission Decision 2000/532/EC (European Communities, 2000). In this document 893 types of waste are divided into 20 chapters, mainly according to economic sector or process of origin (European Comission, 2018). In literature one also can find references to EWC-Stat categories of waste, according to which regulation (EC) 2150/2002 on waste statistics (WStatR) obliges Member States to report statistical data on waste generation and waste treatment for all economic activities covered by NACE REV 2[2] (EPC, 2002). According to EWC-Stat, plastic wastes are aggregated under category 07.4 (European Comission, 2010). The content of this category and the waste types from the LoW that correspond to 07.4 EWC-Stat category can be found in literature (Eurostat, 2010).

Legal definitions of waste types can be found across regulatory literature: WFD and Directive (EU) 2018/851 define non-waste and waste, hazardous waste, municipal waste, construction and demolition waste and bio-waste.

Municipal waste is waste from “households and […] retail, administration, education, health services, accommodation and food services, and other services and activities, which is similar in nature and composition to waste from households”. The same directive corresponds municipal wastes to types of waste included into LoW chapters 15 01 (waste packaging) and chapter 20 (municipal wastes).

Construction and Demolition (C&D) waste is waste produced by construction and demolition activities. It should also include waste produced by private households from “minor do-it-yourself construction and demolition activities”. Construction and demolition waste corresponds to the waste included in chapter 17 of LoW (EPC, 2018).

Packaging waste is regulated by Directive 94/62/EC on Packaging and Packaging Waste (PPWD). The directive and its amendments contain relevant definitions, recovery and separately recycling targets, collection guidelines and limits on concentration of heavy metals in packaging, among other things. Packaging waste is defined as packaging and packaging material described by definition in 75/442/EEC with excluded production residues (EPC, 1994; EPC, 2015). The goal of PPWD is to prevent and decrease the environmental impact of packaging and packaging waste (Eskelinen, et al., 2016).

Packaging is defined by Directive 94/62/EC as “all products made of any materials of any nature to be used for the containment, protection, handling, delivery and presentation of goods, from raw materials to processed goods, from the producer to the user or the consumer” (EPC, 2015). As a group, it consists of primary or sales packaging, secondary or group packaging and tertiary or transport packaging. Plastic is defined within the same Directive as polymer to which additives of other substances were possibly added (EPC, 2015).

End-of-Life Vehicles (ELV) are regulated by Directive 2000/53/EC on end-of-live vehicles (ELV Directive). “Vehicles” included under that directive are passenger vehicles with maximum eight seats in addition to the driver's seat, vehicles for the carriage of good and having a maximum mass not exceeding 3.5 tones and three-wheel motor vehicles except for motor tricycles. Additionally to relevant to ELV definitions and requirements on waste management process, it has the requirements on coding standards that producers should follow (EPC, 2000).

Electric and Electronic Equipment Waste (WEEE) is regulated by Directive 2012/19/EU on Waste Electrical and Electronic Equipment (WEEE Directive). Till 14 August of 2018 categories of EEE covered by WEEE directive were, among other things, large household appliances, small household appliances, IT and communication equipment and toys, leisure and sport equipment

[2] statistical classification of economic activities in the European Community

(non-exhaustive list). After 15 August 2018 the directive will cover all EEE divided into 6 categories based on their size and main function with the exceptions mentioned in the Directive. Waste of EEE is defined using the waste definition by WFD. Apart of definitions, WEEE directive provide guidelines on product design, instructions on collection, treatment and shipment of EEE; defines minimum collection rate and recovery targets and describes information that should be provided for the user. (EPC, 2012)

2.4. Responsibility for waste management

Managing waste, including recycling, comes with expenses. When the product is produced in one point of the supply chain, consumed in another and discarded in the third, comes the question – who is responsible for waste? The responsibility for the waste might mean administrative responsibility for organization of the waste management process or financial responsibility for costs generated by that process.

According to “polluter-pays” principle, the original producer of the waste or current or previous waste holder is responsible for costs, associated with waste management. Nevertheless, a Member state can decide that producer of the product is responsible for such costs, therefore has extended producer responsibility (EPR) (EPC, 2018; EPC, 2008). For example, in Finland such products as packaging, car tires, batteries and accumulators, cars and electronic equipment are subjects to EPR (Ympäristö.fi, 2018).

EPR is attributed to producer or importer of some products and encircles organizational and financial responsibility for waste management of these products. The costs that should be covered by the financial contributions payed by the producer are costs of separate collection, transport and treatment necessary to meet the Union waste management targets and costs of information providing and data gathering (EPC, 2018). In practice the responsible parties usually organize themselves into producer/importer organizations, which are then organizing the waste management of the products included into EPR scheme.

EPR scheme membership can be marked on a product. For example, Green Dot scheme has originated in Germany and are now operating in many EU countries. That trademark, when placed on packaging, indicates that financial contribution for such packaging has being paid by packers/importers to a qualified national recovery organization (PRO Europe, 2018).

2.5. Waste under REACH

Regulation on Registration, Evaluation, Authorization and Restriction of Chemicals (REACH Regulation (EC) No 1907/2006, later in the text REACH) is an important piece of legislation for companies that manufacture and place chemical substances on market in EU. In REACH, definitions of substance, mixture and article are presented, where importance of chemical composition (substance or mixture) or the shape of the object (article) is highlighted. REACH requirements for substances, mixtures and articles do not apply to waste (ECHA, 2010), but since the exposure scenarios that describe manufacturing and use of the substances should include also waste stage, waste is defined in REACH too. Additionally, material that was waste, but ceased to be it, falls within REACH regulation. This will be discussed in more details in the Chapter 3.

Waste can originate from many points in the supply chain. Systematic approach is provided by guidance documentation for information requirements and chemical safety assessment (ECHA, 2012). According to the guidance, potential origin of the waste can be:

- Residues from manufacturing of a substance
- Residues from formulating mixtures and transferring the substance from/to containers further downstream
- Residues from the use of mixtures

- Residues from processing articles (in which the substance has been incorporated) in the production of articles
- Articles at the end of their service life (post-consumer waste)
- Residues from treatment in dedicated waste treatment facilities which are still regarded as waste

In the list above, residues mean the unintentional output of the process (ECHA, 2012), which may be legally waste or non-waste (European Comission, 2012).

ECHA guidance recommends the manufacturer/importer to define one of the three destinations for its wastes: municipal waste, waste for recycling or hazardous waste. Wastes for recycling or recycling waste (RW) are non-hazardous solid wastes that contain substances or materials, which are to be recycled from article waste. The input for this stream can be separately collected waste from consumers and industrial or professional users or off-specifications from downstream users. The wastes that are likely to be recycled are of high value (like precious metals), unchanged or scarcely diluted during use (like glass) or contained in the complex articles for which special legal requirements or voluntary agreements exist to support separate collection and treatment. (ECHA, 2012)

2.6. Non-waste

Under waste legislation, a *substance or object* can be whether waste or non-waste (European Comission, 2012). Sometimes term "product" is used in the waste legislation texts[3] and in everyday language as opposite of waste. Nevertheless, to avoid confusion, "non-waste" should be used as opposite of waste rather than "product" (Kauppila, et al., 2018).

Two categories of non-waste material that can sometimes be confused with waste are by-products and internal waste. As we will see in chapter 3, only waste can be recovered, recycled and become non-waste, therefore for work in hand the division is important.

WFD states that "a substance or object resulting from a production process the primary aim of which is not the production of that substance or object is considered not to be waste, but to be a by-product" once the certain conditions are met (see table 1).

Table 1. *Legal pre-requisites for by-product (EPC, 2008)*

Conditions for classification a material stream as by-product
1. Further use of the substance or object is certain 2. The substance or object can be used directly without any further processing other than normal industrial practice 3. The substance of object is produced as an integral part of a production process 4. Further use is lawful, i.e. the substance or object fulfils all relevant product, environmental and health protection requirements for the specific use and will not lead to overall adverse environmental or human health impact.

Detailed guidelines on classification a residue as a by-product can be found in the literature (European Comission, 2012). By-products can be an important source of secondary raw material, but since they are not legally considered as waste, they are not dealt with within the present work.

Villanueva and Eder mention division of plastic waste into external and internal waste plastic. External waste plastic is collected and/or processed with the purpose of recycling, while internal waste immediately collected and absorbed back into the process without leaving the plant (Villanueva & Eder, 2014).

[3] For example, in Article 8 of WFD "[…] such measures may include an acceptance of returned product and of waste that remains after those products have being used."

Equipped with the knowledge from chapter 2, we can now divide the waste produced by industry, on post-industrial industrial waste and post-consumer industrial waste – a division utilized further in the text. We can also exclude the production residues that can be absorbed back into manufacturing process from post-industrial industrial waste and from waste in general.

3. END OF WASTE CRITERIA FOR PLASTICS

By now, the reader is expected to have an idea, what is waste. As one might notice, becoming waste does not require much – whoever can decide to discard a substance or an object for it to become waste. Let us now examine the opposite process – learn how waste can become non-waste.

3.1. End-of-Waste in European waste legislation

According to Article 6 of WFD, certain specific “waste which has undergone a recycling or other recovery operation” shall ceased to be waste, if it complies with specific criteria developed in line with certain legal conditions (European Comission, 2018). These legal conditions are presented in the table 2.

Table 2. *Legal pre-requisites for EoW candidates (EPC, 2008; EPC, 2018)*

Legal conditions for classification a material stream as End-of-Waste
1. The substance or object is to be used for specific purposes 2. A market or demand exists for such a substance or object; 3. The substance or object fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products; 4. The use of the substance or object will not lead to overall adverse environmental or human health impacts.

The criteria may be developed on three levels:

1. Union-wide criteria developed for specific materials by the Commission. Development of such criteria would result in a high level of environmental protection and a benefit for environment and economy. The aim of Union-wide criteria is further encouraging recycling in the EU through creating legal certainty and removing unnecessary administrative burden. For the moment (July 2018), Union-wide criteria exist for iron, steel and aluminum scrap, glass cullet and copper scrap, but not for plastics (European Comission, 2018). A methodology to develop the criteria for waste plastic was undertaken by Joint Research Centre, although it did not result in any regulation to date. The criteria should include the parameters outlined in the table 3.

Table 3. *Parameters to be included into End-of Waste criteria (EPC, 2008)*

(a) permissible waste input material for the recovery operation; (b) allowed treatment processes and techniques; (c) quality criteria for end-of-waste materials resulting from the recovery operation in line with the applicable product standards, including limit values for pollutants where necessary; (d) requirements for management systems to demonstrate compliance with the end-of-waste criteria, including for quality control and self-monitoring, and accreditation, where appropriate; (e) a requirement for a statement of conformity

2. In case the Union-wide criteria do not exist, Member State may establish detailed criteria on application of conditions mentioned in the table 2 to certain types of waste. The detailed criteria should consider “any possible adverse environmental and human health impacts of the substance or object” and should include parameters mentioned in the table 3.
3. If criterial have been established neither by the Commission, nor a Member State, a Member State can make the decision on a case-by-case basis or evaluate that certain waste has ceased to be waste on the basis of the conditions (see table 2) and reflecting the parameters (see table 3). Decision should be considering limit values for pollutants and “any possible adverse environmental and human health impacts” (EPC, 2018).

It is a first user of the not placed on the market material with terminated waste status or producer of EoW material, i.e. an entity that placed a material on the market for the first time after termination of its waste status, who should ensure that the material meets relevant requirements defined by abovementioned legislation (EPC, 2018). For example, under Council Regulation (EU) No 333/2011 on EoW criteria for scrap metal, the legal condition for reaching the EoW status is transfer of possession from EoW material producer to another holder. It is the producer of EoW material then, who is responsible for providing the evidence that EoW criteria have been fulfilled via statement of conformity (European Comission, 2012).

3.2. Recovery and recycling

The concept of recovery is critical for waste becoming non-waste, as the moment of material or substance reaching EoW is "simultaneous with the completion of the recovery and recycling processes" (European Comission, 2012). Any waste management operation can be classified whether as recovery operation or disposal. Example of disposal is landfilling (EPC, 2008). Primary result of disposal is removal of waste, while principal result of recovery operation is waste serving a useful function or preparation of waste to fulfill useful function (European Comission, 2012). Disposed waste cannot become non-waste (Kauppila, et al., 2018). Recovery operation can be considered completed, when a safe, i.e. not representing any waste-specific risks to health and the environment, and useful input for further processing becomes available (European Comission, 2012).

Recovery is defined by WFD as "any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy" (EPC, 2018). Recycling of organic substances is one example of recovery process, some other examples are listed in non-exhaustive list on Annex I of WFD (EPC, 2008).

WFD defines recycling as "any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes" (EPC, 2008). Using waste as resources, avoiding waste generation and becoming "recycling society" are explicit goals of WFD. Guidance on the interpretation of key provisions of WFD states that "recycling includes any physical, chemical or biological treatment leading to a material which is no longer a waste" (European Comission, 2012). The recycling can therefore be understood as the recovery process, which converts waste into non-waste. On the other hand, if processing of waste still results in waste, which consequently undergoes other recovery steps, such processing should not be considered recycling, but "pre-treatment prior to further recovery" or "preparation prior to recovery or disposal' or "pre-processing prior to recovery" (European Comission, 2012). Recycling can be also understood then as process of production of secondary raw material. According to guidelines, for material with terminated waste status, no additional waste treatment stages should be needed, and the material should be ready for the final use (European Comission, 2012). That practical definition might be useful, as despite extensive referencing, a concept of s*econdary raw material* is not defined clearly in any European Community legal text (EU Science Hub, 2018).

Waste ceases to be waste, when a safe and useful product is placed on the market (Villanueva & Eder, 2014). EoW criteria define the specifications that the waste stream has to fulfill in order to cease to be waste. The legal conditions for changing waste status are fulfilled somewhere along the processing chain, resulting in recovery of the waste and production of non-waste.

Villanueva and Eder refer to mechanical recycling as processing of plastic waste by physical means into plastic product and include grinding, shredding and melting into parts of the process (Villanueva & Eder, 2014). The same authors describe reprocessing as a broader term used to define any of the intermediate actions in the waste plastic chain between end-users and the plastic converters and including activities such as collection, sorting, classifying, baling or transportation.

The text below describes reprocessing of the waste from the beginning of collection all the way into production of pellets by means of mechanical recycling.

In Europe, collection of industrial, agricultural and construction waste is usually performed by private companies and collection of municipal solid waste – by municipalities. Household plastic waste can be collected as plastic material (single plastic or mixed plastic), together with other dry recyclable materials or together with municipal solid waste. Recyclables - plastics only or mixed with other dry recyclables - can be collected either by kerbside collection/ door-to-door collection or at drop-off locations. In kerbside collection, the citizens are placing recyclables into specified bins/bags, which are then emptied/collected from each household. For collection at drop-off locations, the citizens are required to collect their recyclables and bring them to the specified location. For some types of recyclables (i.e. beverage bottles), deposit refund system can be used, where the consumer receives back the surcharge included into the price of the beverage, once the bottle is returned. (Villanueva & Eder, 2014).

Collected plastics can be contaminated due to the nature of the waste or from the processing stages. Bonded contamination like glues or embedded like ingrained soil is difficult to remove. Complete removal of chemical contamination usually requires desorption, which is a slow process. Due to the challenges associated with contamination, plastic recyclers try to keep the streams as specific and separate as possible (Villanueva & Eder, 2014).

Unless collected plastic is free of contaminants and polymer-type/color separated, sorting/pre-treatment is usually required. Sorting/pre-treatment step is denoted as one, as for example, plastic packaging waste can go through one of few sorting operations, while for WEEE dismantling, shredding and sorting would be included in that step (Deloitte, 2015). During that stage, the waste plastic is separated from non-plastic content and often divided into polymer categories. Sometimes it is also classified by color. Insufficient sorting can lead to a mix plastic fraction for which recycling is not economically feasible nor suitable or/and results in safety or health risks. Sorting can be either manual or automatic. Automatic sorting is usually more effective, when supplemented by some degree of segregation at source of packaging from bio-waste. Most of the sorting technologies are based on three properties of materials – magnetic, density and spectrophotometric. Magnetic separation is used for separation of ferromagnetic metals, while eddy current separators are used for non-ferromagnetic ones. Examples of density separation techniques are air classifier, flotation sorting, centrifuge and cyclone. Other common sorting techniques are optical sorting based on use of optical sensors and techniques based on near-infra red (NIR) spectroscopy and Raman spectroscopy. (Villanueva & Eder, 2014).

The basic processes that can be considered a part of mechanical recycling of waste into pellets are

- cutting of large plastic parts into pieces
- shredding of these pieces into flakes for easier separation and cleaning
- sorting and cleaning of the flakes
- extrusion of flakes/pellets/agglomerates into strands with or without filtering of the melt
- cutting of strands into pellets (Villanueva & Eder, 2014).

These processes are not compulsory sequential, neither all of them take place at each mechanical recycling event. Usually referred to as *separation, further separation or flake-separation*, second sorting is usually performed on shredded plastics and often utilizes floatation techniques and optical sorting techniques (Hopewell, et al., 2009). In addition, adsorbed chemical contamination such as oils, solvents, foodstuff or detergents will require cleaning. Cleaning usually involves washing with hot and cold water and sometimes detergents/alkali, usually under agitation (Villanueva & Eder, 2014).

After complete recycling chain, the material contains little contamination and can be used in a plastic conversion process to replace virgin materials without further processing. Output of mechanical recycling process can be pellets or articles. In EU in approximately 13% of cases plastic articles, rather than pellets, are produced (Villanueva & Eder, 2014).

Size reduction and separation processes are described in detail elsewhere (Vesilind, 2003; Ronkanen, 2016). The whole process of mechanical recycling of plastics is also described in details in plenty of sources (Eskelinen, et al., 2016; Hiipakka, 2011; Aaltonen, 2014; Hiljanen, 2014; Poropudas, 2011).

3.3. Methodology of material status assessment

Unfortunately, none of the formally existing waste sub-streams is named “Suitable to become non-waste”. In order to explore, what makes a suitable EoW candidate, we shall learn about history of EoW assessment for plastics and explore how the waste can be divided into potentially suitable and non-suitable for waste status assessment sub-streams.

In 2010, Joint Research Center (JRC) has published a report, presenting a list of waste streams containing secondary material that would be suitable candidates for detailed assessment of EoW criteria[4]. As it was mentioned earlier, by 2018 the EU-wide criteria for few material streams does already exist, but in 2010, the work was only starting.

Several potential sources of recyclable materials were excluded from the assessment for suitability as EoW candidate. Non-recoverable hazardous waste, agricultural waste left on land after harvest, surplus products unreturnable to supplier and by-products were among the excluded sources (Villanueva, et al., 2010).

The report (Villanueva, et al., 2010) made a distinction between waste streams and materials in them – the processing of one waste stream can result in generation of a few material streams, some of which may be a suitable replacement for virgin material and can be therefore called secondary material and be selected for EoW candidate, while some would be waste. The distinction is important, as EoW may apply to certain applications of some of the outputs, not to initial waste stream and all its outputs, says the report.

In the course of project described in the report (Villanueva, et al., 2010), 60 waste streams containing secondary material were identified through a literature search and the list was reduced to 20, based on the data availability. These 20 streams were ranked and assigned to one of three categories, based on the suitability of the stream as candidate for further EU-wide EoW assessment. Plastics were among the material streams scoring the highest due to being raw material used in industrial processes and for which the risk to health and environments damage are controlled through industrial permits. Other streams with high scores were metal scrap of iron, steel and copper[5], paper, textiles, glass[6], metal scrap of zinc, lead and tin and other metals. The materials mentioned were proposed as priority materials for EoW assessment based on their composition, level of contamination and market in EU (Villanueva, et al., 2010).

Aggregated EU stream of plastics potentially suitable for EoW assessment consisted of plastic waste included into MSW, manufacturing waste, plastics in construction and demolition waste or ELVs and separately collected plastic waste, including plastic packaging waste. The challenge in data aggregation was encountered, as same plastic streams could be collected within different fractions in Europe (Villanueva, et al., 2010)

The report by Villanueva et al. was produced in an effort to choose suitable material streams as EoW candidates from *all materials.* As a result, the material streams – such as plastics – were identified, but more detailed assessment was further required in order to identify the sub-streams

---

[4] Here not only plastics but all materials were evaluated for their suitability as EoW candidate
[5] EU-wide detailed criteria for EoW acceptance exists by 2018
[6] EU-wide detailed criteria for EoW acceptance exists by 2018

of plastic waste stream, which would make a good candidate for non-waste. As it is described in the report, the first task of the actual material status assessment would be disaggregation of the waste streams into categories with high value recyclables and identification of low-value sub-fractions containing contamination detrimental to environment and processing and not qualifying as EoW candidate (Villanueva, et al., 2010).

The next report, a technical proposal “End-of-waste criteria for waste plastic for conversion”, written by two of the authors of the aforementioned report was published in 2014. The scope of the technical proposal was waste plastic reprocessed into an input for re-melting in the production of plastic articles. EU-wide EoW criteria were proposed for the waste plastic that has undergone all or part of the conversion processes[7]. The direct conversion into articles was excluded from the scope of the report, as well as processing of plastic types that cannot withstand conversion. The ultimate aim of the criteria was product quality. Additional requirements on input material and processing techniques, as well as requirement on quality assuring system were included to ensure the product quality. (Villanueva & Eder, 2014)

The term “waste plastic” was used by Villanueva and Eder to describe “plastic from industrial or household origin which is collected, sorted, cleaned and in general reclaimed and processed for recycling” (Villanueva & Eder, 2014). Some other terms can be used to refer to some or all types of waste plastic. Association of European plastic recyclers defines recyclate as “material resulting from the processing of plastic waste” (Plastics Recyclers Europe, 2018). Term “plastic scrap” is often used in the EU to describe post-industrial waste, while in US it can mean post-consumer waste (ISRI, 2018).

Table 4 presents forms of waste plastic, as presented by Villanueva and Eder. Particle size is given only for direction. Additionally to the forms mentioned, waste PVC is usually processed into powder form.

Table 4. *Forms of waste plastic and their description (Villanueva & Eder, 2014)*

			
Bale or bulk Collected articles as they are or after sorting	**Regrind/flake** Shredded material. Typical particle size below 2.5 cm	**Agglomerate** Mechanically or thermally denisfied film, typical particle size 3*2*3 cm	**Pellet** Standard raw material form used in plastic manufacturing and conversion. Typical size 0.2*0.2*0.2 cm

3.4. Proposed EU-wide EoW criteria

In the previous section we examined how and why the plastic stream was chosen from the total waste stream as candidate for termination of waste status. We are now half-way through our second objective – examining the conditions for termination of waste status. As we know by now, EU-wide criteria for termination of waste property of the plastic was proposed, but currently does not exist. That means that recycler cannot compare the waste she/he recovered with any EU-

[7] Here by conversion processes Villanueva and Eder meant processes included into transformation of waste plastic material by application of pressure, heat and/or chemistry into finished or semi-finished products for industry or end user.

wide specifications to declare that recovered material is non-waste. In this sub-chapter we explore, what would be expected from recycler, if proposal by Villanueva & Eder were implemented in legislation.

Villanueva & Eder provide the detailed requirements for the plastic waste and waste plastic, recycling process and documentation - components shaping the properties of the potential non-waste plastics (Villanueva & Eder, 2014), which are visualized on figure 2.

Figure 2. *Four components of the waste plastic recovery system subjected to requirements: incoming waste, recovery process itself, resulting waste plastic and quality assurance during the process*

Based on the requirements proposed (Villanueva & Eder, 2014, pp. 159-179), the EoW criteria for the output resulting from the recovery process would be the following:

- compliance with customer or industrial specifications for direct use in the production of plastic items or substances through re-melting in plastic manufacturing facility
- non-plastic content of maximum 2% of moisture-free weight
- safety, i.e. classification as non-hazardous according to CLP regulation, compliance with conditions of commercialization of substances of very high concern (SVHC), compliance with restriction of commercialization of persistent organic pollutants (POPs) and exclusion of any leachable fluids and fatty foodstuffs

Requirements for the incoming waste, processing and management systems are provided as important supporting blocks of the recovery system resulting in non-waste (Villanueva & Eder, 2014):

- The incoming waste material for the recovery operation would be expected to
    a. not include bio-waste, health care waste and used personal hygiene products
    b. not be classified as hazardous, according to waste legislation, unless the proof can be provided that the processing involved removes all hazardous properties
- During the recovery process
    a. the waste intended as an input would be expected to be stored separately from other wastes, including other waste plastics grades
    b. all the processed required to provide the waste plastic in the free-flowing form suitable as input for manufacturing of plastic products would be expected to be completed
    c. plastic waste input from WEEE and ELV containing hazardous components would be expected to undergo all the treatment required by WEEE or ELV directives
    d. all hazardous waste not previously mentioned would be expected to be removed
- The manufacturers would be expected to produce a statement of conformity for each consignment of waste plastic

As the recycler would be expected to self-monitor the quality of the input, output and the process itself, its management system would be expected to be transparent and appropriately certified. It would be expected to include a set of procedures on how the quality of the output is sampled and analysed, how the treatment process is monitored, how the input waste is controlled, how the feedback from the customers (recyclate converters) is collected, how records regarding all previously mentioned procedures are kept and stored, how the system itself is reviewed and improved and how the stuff is trained. (Villanueva & Eder, 2014, pp. 175 - 179)

In order to comply with requirements described, the recycler's qualified stuff would have to inspect all incoming plastic-containing waste (especially WEEE and EVL) and accompanying documentation for compliance. Mixing of possibly hazardous materials with the rest of the stream would have to be avoided. Finally, qualified personnel would have to verify that each batch of the waste plastic complies with appropriate specifications. The waste plastic would have to be visually assessed on presence of non-plastic contamination and periodically[8] analysed gravimetrically for the content and nature of non-plastic components. Compliance with REACH and CLP regulations would have to be assessed based on quantitative and qualitative characterisation of the recycled material. (Villanueva & Eder, 2014, pp. 175 - 179).

In absence on EU-wide criteria, the mechanisms of transfer of waste plastic into non-waste will vary from country to country and from case to case. For example, in England, which is regarded as one of the advanced countries with respect to application of EoW legislation, the rules for how a specific waste stream becomes non-waste are defined in Quality Protocols (QP). Only materials processed or manufactured in facilities with environmental permits can become non-waste. Each QP is developed in cooperation of Environmental Agency and industry and is based on a technical report. The technical report is usually based on background analysis on degree of substitution potential of virgin material with waste-derived material, analysis of economic impacts and risk analysis. (Kauppila, et al., 2018). Despite a substantial work behind QP, the result is concise, easy to read instruction-like text. The quality protocols, for example, for non-packaging plastics, prescribes, among other things, that the products made from the waste can be used only for manufacturing of plastics, that the records of the processes are to be kept for 2 years and that Safety Data Sheet (SDS) is to be prepared for the customer (Environmental Agency (UK), 2016).

Unfortunately, no material- or waste stream-specific methodology for termination of waste status of any plastic waste is available in Finland for the moment. As the result, a manufacturer of a non-waste material is presented with uncertainties related to procedure of decision-making process, its output and costs associated with the process, scope of application and requirements to the post-use of the material. Additionally, the manufacturer should be aware of regulations related to both waste status and non-waste status of the material. (Kauppila, et al., 2018)

In Finland, the decision regarding change of material status is made by permitting authority (AVI or ELY) and based on the application provided by waste processor in the environmental permit (Kauppila, et al., 2018; Pekki & Liski, 2017). In this application, the waste processor documents that the conditions for ceasing the waste status has been fulfilled (Salminen, 2018). The work on common methodology for termination of plastic waste status in Finland is scheduled to be started in 2019 (Salminen, 2018).

[8] The frequency of monitoring would be dependent on expected pattern of variability and inherent risk of variability in the input, inherent precision of the monitoring method and proximity of the measurement results to the limit value (Villanueva & Eder, 2014, p. 161).

4. MARKET, SAFETY AND QUALITY OF WASTE POLYOLEFINS

In order to assist a Finnish manufacturer of a recycled plastic, who attempts to terminate the waste status of produced material, the Chapters 4 and 5 present an overview, which might be used as background information for such an attempt. Additionally to the purpose of serving as base for the application, the overview pinpoints potential method for delivering such information.

4.1. European waste plastic market

Non-waste material has to be used for specific purposes and a market or demand should exist for it. Compliance with these two conditions can be indicated by:

- The existence of firmly established market conditions related to supply and demand
- A verifiable market price being paid for the material
- The existence of trading specifications or standards (European Comission, 2012).

4.1.1. Glimpse on EU recycling market in 2013-2018

In 2014 Villanueva and Eder described the market of waste plastics as small and immature, if compared to virgin plastics. The link between the supply and demand was not direct, neither the prices of the reprocessed material were determined by the production cost. Instead, prices of the virgin and reprocessed materials were linked. Lack of sufficient supply or capacity prevented maturation of the market. Use of recycled polyethylene terephthalate (PET) in fibers and recycled high-density polyethylene (PE-HD) in various applications were presented as examples of well-functioning markets (Villanueva & Eder, 2014).

Let’s next explore the situation in more details.

Plastic industry can be considered consisting of few types of actors – plastic manufacturers, converters, machine manufacturers and recyclers (APM, 2018). Manufacturers produce plastics from raw materials supplied within chemical industry. Converters buy their raw material in granular or powder form and use conversion processes[9] to provide a wide range of semi-finished and finished products for industrial and consumer markets. Recyclers take care of plastic waste processing. (Debergh, et al., 2015) Recycling sector might include plenty of actors such as collecting and sorting entities, crushers, conditioners, brokers and (re)converters (Villanueva & Eder, 2014). Plastics are available for converters in different grades – often based on property-modifiers added, viscosity, fireproofing characteristics, chemical organization of the polymer chain or food compliance. In some applications, for example flexible packaging, combination of a few plastics or plastic with other materials is processed by converters (Deloitte, 2017). In 2013 plastic industry in EU comprised around 61 000 companies employing 1.4 million people. In the same year the estimated number of plastic recyclers was 1000, employing 30 000 people (Debergh, et al., 2015).

In 2016, the total production of plastic industry in EU was around 60 Mt. Exported and imported amounts for that year were not available for the author, but in 2012, around 27% of produced plastics were exported and around 13% - imported (Debergh, et al., 2015). In 2016 EU converters consumed 49.9 Mt of plastics, with almost 20 Mt being consumed by packaging sector and building and construction (B&C) sector being the second largest user (APM, 2017). Figure 3 below depicts EU plastic converters demand by sector.

[9] Conversion processes here are processes such as film extrusion, injection molding, blow molding or rotomolding.

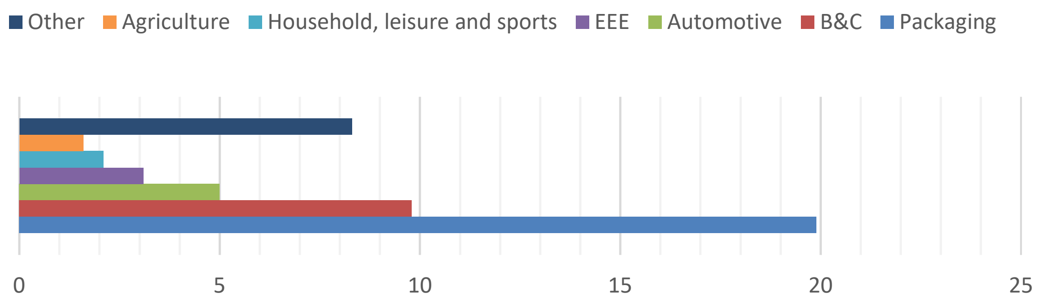

Figure 3. *Plastic converter demand by segment in million metric tons (Mt) (APM, 2017)*

Eventually all the items produced from plastics become waste. It is estimated that around half of plastic products have short life span, therefore expected to become waste soon after production. Packaging, single-serve articles and agricultural films are examples of such products (Eskelinen, et al., 2016; Hopewell, et al., 2009). Around 20-25% of the plastic products is estimated to have long lifespan. Example of those are pipes, cables and structural materials. The remaining 25-30% of products have intermediate lifespan. Examples of those products are vehicles, furniture and electronics goods (Hopewell, et al., 2009).

Main identified source of plastic waste is plastic packaging waste (PPW). Others major identified plastic waste streams are plastics wastes in Municipal Solid waste (MSW), Construction and Demolition waste (C&D), agricultural waste, Waste Electric and Electronic equipment (WEEE) and End-of-Life Vehicles (ELVs). (Delgado, et al., 2007; Villanueva & Eder, 2014; Hopewell, et al., 2009; Eskelinen, et al., 2016)

According to Deloitte, around 28.2 Mt of post-consumer plastic waste would be generated in EU in 2020. The estimations are based on the amounts generated in 2012 and annual growth rate predictions made by industry (Deloitte, 2015), as presented in table 5.

Table 5. *Distribution of plastic waste by source in Europe in 2012 and annual growth rates (Deloitte, 2015). Only the plastic contained in the waste stream is referred to by the name of the waste stream.*

Plastic waste stream	**Amount (kilotonnes)**	**Fraction of total amount (%)**	**Annual growth (%)**
Packaging	15876	63%	1%
WEEE	1260	5%	3.5%
ELV	1260	5%	2.5%
B&C	1512	6%	2%
Agricultural	1260	5%	0.5%
Other plastic waste	4032	16%	2%
TOTAL	25200	100%	1.4%

The overall recycling rate for plastic in Europe is 31.1% (EPRO, 2017; APM, 2017). For plastic packaging the recycling rate reached 40.9% (EPRO, 2017). Consequently, industrial statistics on plastic recycling suggests that in 2017 in Europe around 8.4 Mt of plastic waste was recycled, of which 6.8 Mt plastic were packaging.

Difference in recycling rates for post-consumer and post-industrial plastic can be highlighted. In OECD report, a 33% material recycling rate of post-consumer plastic waste was reported for Germany. The same report states the recycling rate of post-industrial waste to be 80% and attributes the difference to high quality of this fraction (OECD, 2010).

Ideally, recycling industry strives to produce the recycled plastic for the same applications it originally had through closed-loop recycling. The choice is easy, as the plastic has already been purposefully used for an application and commercialized, therefore it is easier to use the existing functionality of the plastic and meet technical and legislative requirements. Recycling of PET bottles is an example of one successful closes-loop recycling. However, due to expensiveness of closed-loop systems, polymers are often “downcycled”, i.e. recycled into cheaper and less demanding applications. In 2014, a typical application of a recycled plastic was a dark plastic film or non-food packaging container (Villanueva & Eder, 2014). Based on the market survey performed within W2PLAST project, a recycled plastic used as secondary raw material finds its place in non-visible, non-colored application, which does not have to bear the load, does not have to be further processed and does not represent a known brand (EC, 2014)

4.1.2. Closer look – plastic packaging waste

In 2012, plastic packaging waste (PPW) comprised 63% of all plastic wastes in Europe (Merta, et al., 2012; Deloitte, 2015). In 2016, PPW constituted 16.7 Mt, i.e. around 62% of all plastic waste collected (APM, 2017). Industrial statistics of 2017 indicates that of post-consumer plastic packaging 64% originated from households and remaining 36% - from commerce and industry (EPRO, 2017).

Composition of PPW stream is country- specific. For example, PPW in Austria consists of separately collected plastic packaging and packaging recovered from MSW and bulky/commercial waste (Van Eygen, et al., 2018). In Netherlands, post-consumer PPW for recycling consists of separately collected packaging from households, mechanically recovered plastic from MSW and large PET bottles collected through deposit-refund system (Brouwer, et al., 2017; Thoden Van Velzen, 2015). PET bottles in Netherlands are officially treated and registered as post-industrial packaging waste (Brouwer, et al., 2017).

Composition of PPW in Austria in 2013 analysed by Van Eygen et al. is presented in the table **6,** where percentages of polymer types are presented in the lowest row and fractions of product categories – in the last column. More than a half (58 ± 3%) of PPW stream was collected separately, the rest is discarded into municipal solid waste or into bulky and commercial waste (Van Eygen, et al., 2018).

Table 6. *Product categories and polymer types in plastic packaging waste in Austria. Total amount of PPW generated in 2013 was 300,000 ± 3 % tones/year (Van Eygen, et al., 2018).*

	LDPE	**LLDPE**	**HDPE**	**PP**	**PS**	**EPS**	**PET**	**PVC**	**Total (product categories)**
Large films	mostly	some	-	-	-	-	-	-	24%
Small films	mostly	some	-	-	-	-	-	minor amounts	24%
Small hollow bodies	-	-	part of	mainly	part of	-	-	minor amount	17%
PET bottles	Only composed of PET, HDPE bottle cups are counted within HDPE category								15%
Large hollow bodies	-	-	equal amounts		-	-	-	-	6%
Large EPS	Only composed of EPS								1%
Others	mainly	present	mainly	present	present	present	mainly	present	13%
Total (material composition)	46 ± 6%	5 ± 5%	11 ± 6%	14 ± 6%	3 ± 5%	2 ± 4%	19 ± 4%	<1 ± 6%	100%

According to Van Eygen et al., recycling rates within packaging sector are relatively high, comparing to other consumption sectors such as building and construction and electronics, which could be explained by the lower use of potentially problematic substances and long-standing legislation behind separate collection of plastic packaging waste. The team estimated that in 2013 in Austria recycling rates for PPW[10] were 39% for large films and 18% for small films with total 25% for PPW (Van Eygen, et al., 2018).

4.1.3. Recycling rates and efficiencies of the steps

In section 4.1.1 we learned that in EU, plastic packaging recycling rate is almost 41% (EPRO, 2017). On the other hand, based on calculations made by Deloitte[11], recycling rate for plastic packaging is 30**%.** Recycling rate for plastic packaging excluding export and contamination is 13% (Deloitte, 2017). So, what is the recycling rate and why the numbers differ so much?

The recycling rate (R) can be calculated based on the equation 1 presented (Deloitte, 2015):

$$Recycling\ rate = \frac{Waste\ sent\ to\ recycling}{Generated\ waste} * 100\%\ (1)$$

Amounts calculated in such way include both plastic waste that is rejected during the process of recycling and never makes it as secondary material and the waste exported for the purpose of recycling (Deloitte, 2015). Recycling rates based on input in recycling plants overestimates recycling rates (Obermeier & Lehmann, 2017). Efficiency of the reprocessing plants is less than 100% and around 20-50% of waste plastic mass is removed as impurities (Villanueva & Eder, 2014).

In Draft COM (2014) 397 targeted recycling rates (recycling targets) are calculated based on the output of the recycling process, which is related to generated waste, unless otherwise specified (Deloitte, 2015, p. 11):

$$Recycling\ rate = \frac{Output\ of\ the\ recycling\ process}{Generated\ waste} * 100\%\ (2)$$

Therefore, the meaning of “recycling rate” and amount of material described as “recycled” in the literature might vary, depending on the method used for the calculations. Villanueva & Eder estimated that of 6.3 Mt post-consumer plastic waste reported in 2011 in EU as recycled, only 3.5 - 4.5 Mt were finally available as secondary raw material for plastic conversion (Villanueva & Eder, 2014). Debergh et al. estimated that of 6.6 Mt of post-consumer plastic waste collected in 2012 for recycling, around half was sent for recycling, while other half was exported to outside Europe (mainly China). Processing of 3.2 Mt of plastic wastes resulted in 1.9 Mt of recyclates (Debergh, et al., 2015). Finally, Debergh, et al. estimated that recycled plastic constituted 4% of 2015 demand for plastic (Debergh, et al., 2015).

Table **7** presents the recycling targets used in a report by Deloitte assessing the impacts of these targets**.** Targets are presented for waste streams containing waste plastics. The sources of these targets are COM (2014) 397, Directive 2012/19/EU, Directive 200/53/EC and voluntary industrial targets. Detailed rationale behind the targets presented can be found in the source report and targets are calculated according to equation 2.

---

[10] Recycling rates calculated as output of recycled facilities/PPW generated, see section **4.3.1**

[11] In its calculations made in 2014, Deloitte has extrapolated the numbers for 6 Member States generating together almost 70% of plastic waste in EU for the whole EU.

Table 7. *Plastic recycling targets used by Deloitte in impact assessment of increased EU plastic recycling targets (Deloitte, 2015).*

Plastic waste stream and process to which the target applies	Target (2020)
PPW recycling	45%[12]
WEEE recycling (of collected waste)	45%
WEEE collection	85%
ELV recycling	30%
B&C recycling (voluntary)	36%
Agricultural recycling (voluntary)	30%
Other plastics recycling	5%
Combined	36%

Attaining the targets presented above would require substantial increase in the efficiency of the collection and sorting processes. For example, if fraction of collected for recycling PPW in all PPW is estimated to be 41 % in 2012 (see figure 4), it has to increase to 70% to attain the 45 % recycling target (Deloitte, 2015).

Two other terms that might be confusing, when navigating plastic-waste related literature, are *plastic waste collected* and *plastic waste generated*. According to industry reports, in 2016, 27.1 Mt of plastic post-consumer waste was *collected* in Europe (APM, 2017), while according to estimations by Deloitte, 25.2 Mt of post-consumer plastic waste was *generated* in EU in 2012 (Deloitte, 2015). In order to understand to what these numbers refer, let's explore the efficiencies of the recycling steps. In their assessment report, Deloitte presents the modeling of the recycling process. Efficiencies of the processes in the recycling chain are calculated using assumptions made by industry and existing data. Estimated efficiencies of process steps involved into recycling of major plastic waste streams are presented on the figure 4. In this figure generated amounts of plastic waste in each waste stream ($\boldsymbol{N_i}$) are taken from year 2012 (see table **5**) and set to 100%. According to the model by Deloitte, only certain fraction of generated plastic waste is collected and sent to recycling, while the rest ends up incinerated or landfilled. The collection rates are calculated from actual amounts of corresponding plastic waste sent in 2012 for recycling and sorting/pre-treatment process yield (see equation 3):

$$\text{"}Sent\ to\ recycling\text{"}\ rate = Collection\ rate * sorting\ yield \quad (3)$$

(Deloitte, 2015, p. 20)

In figure 4, $\boldsymbol{N_{col}}$ indicates the fraction of plastic waste available after collection step and $\boldsymbol{N_{sort}}$ indicates the fraction of waste plastic in each waste stream available for the further recycling after pre-treatment or sorting. Finally, $\boldsymbol{N_{rec}}$ presents the fraction of the generated waste that is available as secondary raw material. Dotted line (Rt) represent the theoretical recyclable share of plastic packaging waste. (Deloitte, 2015)

[12] In 2015 EC has proposed a 55% recycling target for PPW by 2025 (European Comission, 2018).

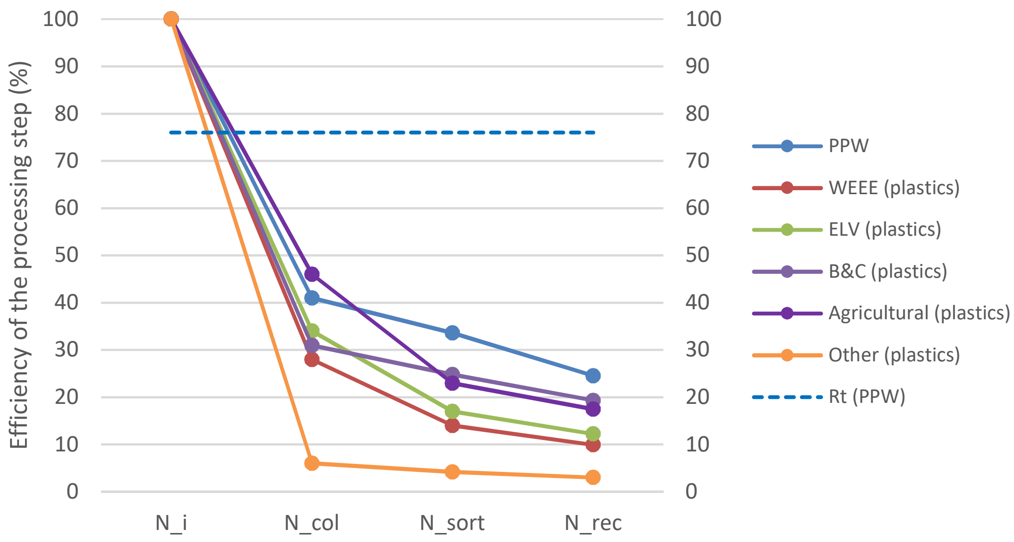

Figure 4. *Efficiencies of the steps in the recycling process in 2012. N_i is initial amount of plastic waste available; N_{col} is fraction available after collection stage; N_{sort} is fraction available after sorting/pre-treatment stage; N_{rec} is fraction available after recycling stage. R_t is theoretical recycling efficiency of PPW (Deloitte, 2015)*

Now, referring back to a few paragraphs, we can assume that 27.1 Mt of plastic post-consumer waste collected in EU (APM, 2017) refer to the same amount as 25.2 Mt of post-consumer plastic waste generated (Deloitte, 2015), as the first source provides the amount of plastics collected from the waste streams, which are therefore generated as plastic waste.

4.1.4. Demand for waste polyolefins

Abundancy and sources of waste polyolefins were estimated by Delgado et al. In Europe low-density polyethylene (PE-LD) was estimated to be the most abundant polymer in waste, due to its major contributing role to plastic packaging. High-density polyethylene (PE-HD) and polypropylene (PP) were estimated to be the second and the third most abundant (Delgado, et al., 2007). For example, in Germany PE-LD/LLD constituted 26.1% of total waste plastics, PE-HD 12.4% and PP 16.4% (OECD, 2010).

The main source of waste polyolefins was estimated to be MSW. Additionally, significant sources for PE-LD were estimated to be agricultural waste and packaging, for PE-HD – packaging and C&D waste and for PP – packaging, ELVs and WEEE (Delgado, et al., 2007). In a study performed in 2014 in Netherlands, C&D waste was identified as an important and attractive source of polyolefins due to well-defined limit in densities of the grades used in construction and as a result a possibility to relative easily separate PP and PE (EC, 2014).

Deloitte estimated that around 61.5% of polyolefin & PET wastes are produced by households and the rest – by industry/commerce (Deloitte, 2017).

Polyolefins, among other plastics, emerge from the generated and collected plastic waste as the output of the sorting step. In table 8 the estimated fraction of polyolefins available as the output of the sorting/pre-treatment process is presented.

Table 8. Breakdown of the plastic resins in the waste streams, output of sorting/pre-treatment, 2012 (Deloitte, 2015, p. 27)

Resin	PPW	ELV	WEEE	B&C	Agricultural	Other
PET	34%	0%	0%	0%	0%	0%
PE-HD	**15%**	**8%**	**2%**	**12%**	**27%**	**9%**
PE-LD	**21%**	**0%**	**0%**	**2%**	**68%**	**25%**
PP	**17%**	**43%**	**27%**	**0%**	**3%**	**10%**
PS	3%	0%	22%	0%	0%	19%
PVC	1%	3%	4%	62%	0%	2%
Other	8%	46%	45%	24%	2%	35%

During mechanical recycling plastic waste can be reprocessed in an article or granulate. In approximately 13% of cases plastic articles, rather than pellets, are produced as a result of mechanical recycling process (Villanueva & Eder, 2014).

When recycled polyolefins are available as pellets and are technically sound and safe to use, one can compare the demand for recycled polyolefins with demand for virgin ones. In 2016 virgin polyolefins constituted 49.1% of EU plastic demand, with polypropylene (PP) converters demanding 9.6 Mt (19.3%), low density polyethylene (PE-LD and PE-LLD) - 8.7 Mt (17.5%) and high density polyethylene (PE-HD) - 6.1 Mt (12.3%) (APM, 2017). A non-exhaustive overview of virgin polyolefin applications is presented on figure **5.**

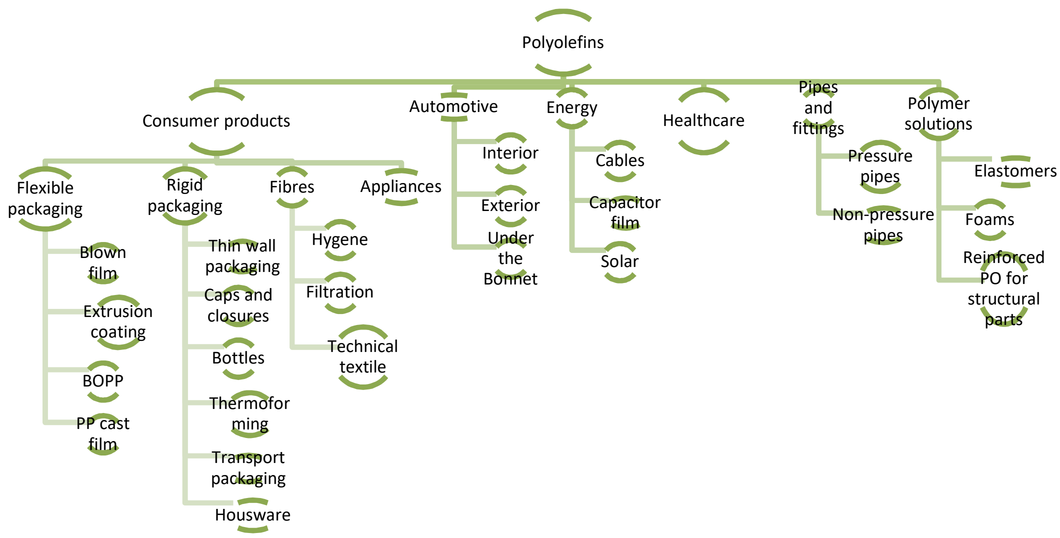

Figure 5. *Non-exhaustive overview of PO applications (Borealis, 2018)*

According to Villanueva and Eder, in 2014 recycled PE-HD was typically used for containers, industrial wrapping and film, houseware and toys. Recycled PE-LD was used for films, bags, coatings, containers, pipes, toys and cable insulation. Recycled PP was used in films, battery cases, crates, car parts and electrical components. Polyolefins were often co-processed, due to difficulty in identifying and separating PP as a separate stream (Villanueva & Eder, 2014). In 2014 it was estimated that in EU the main source of the recycled polyolefins was post-industrial plastic waste (EC, 2014).

From almost 14 Mt of PO & PET of PPW generated in EU[13] in 2014 as household and industrial/commercial waste, around 1.7 Mt of secondary PO were generated (Deloitte, 2017). That amount was related to the converted demand by sector. Total demand for PO for that year constituted 25.9 Mt. The PPW-derived PO use as secondary raw material in various applications is illustrated on figure 6**.** The figure is based on the Sankey diagram of the PPW flows available in the Deloitte report (Deloitte, 2017, p. 16). Estimations show, that in 2014 demand of secondary PPW-derived POs in packaging sector was smallest (2.8% of virgin PO), while demand in C&D sector – highest (16.7% of virgin PO). Demand in automotive and electronic sector were average – with 5.8% and 4.6% respectively. For "Others" sector, no separate figures for PO and PET were available, so stream of secondary PO combined with small amount of PET is used. Demand for PPW-originated PO in "Other" applications was among the highest (11.6%).

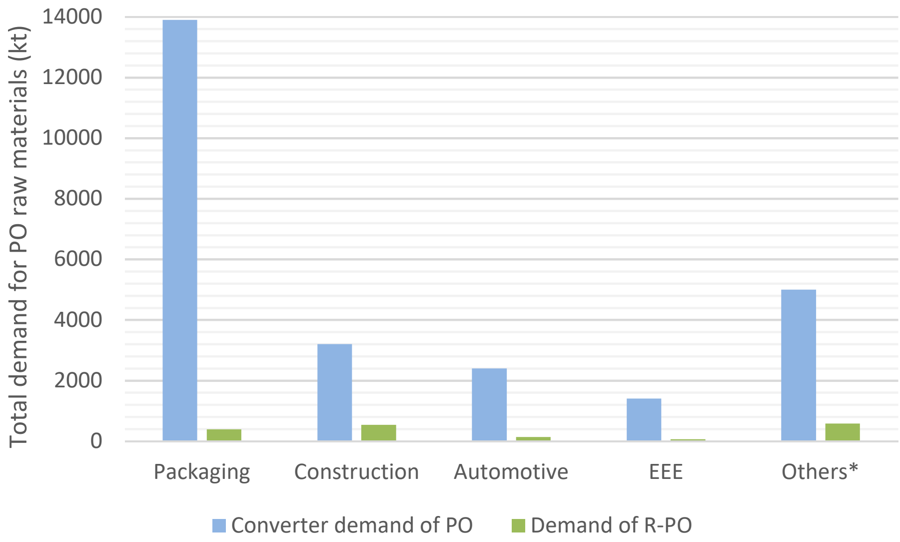

Figure 6. *Fraction of converter demand by sector satisfied with PPW-originated secondary PO (Deloitte, 2017) *On "Others" also PET is included both in Converter demand and in secondary plastic amount, but its amounts are significantly less than POs*

4.1.5. Cost of recycling and price of recycled plastics

Volumes of exported waste plastics can be significant. According to analysis of European foreign trade statistics, in 2015 around 680 kt/month[14] of secondary plastic[15] was traded in Europe. Since 2002, the trade volumes of waste plastic increased 3-4 times (see figure **7**)**.**

On figure 7 a price indicator is value (in €) of all waste plastic with relevant foreign trade statistic codes divided by volume (in tons) of that plastic. The price indicator for EU internally traded EU plastic has stayed in 2002-2016 above the price indicator of extra-EU-28 imported material and material exported outside the EU (Eurostat, 2010), what implies the higher quality of waste plastic traded on the internal market.

When comparing the price indicator to the prices of waste plastic reported by Deloitte, it can be noticed that it is closer to the price of the sorted waste plastic. The price of recycled plastic is higher, in the range of 650-1000 €/t. Reference price range for the virgin plastics is 950 – 1950 €/t (Deloitte, 2015).

Estimations of average European cost of recycling of waste plastic streams are presented on figure **8** and amount of people required for processing of 10 000 tones – on figure **9.**

[13] The numbers for six Member States were extrapolated for the whole EU
[14] 680 kt/month * 12 = 8160 kt or 8.2 Mt/a
[15] Secondary plastic here is "waste materials collected for recycling and recycled materials that can be used in manufacturing processes instead of or alongside virgin raw materials" (Eurostat, 2017).

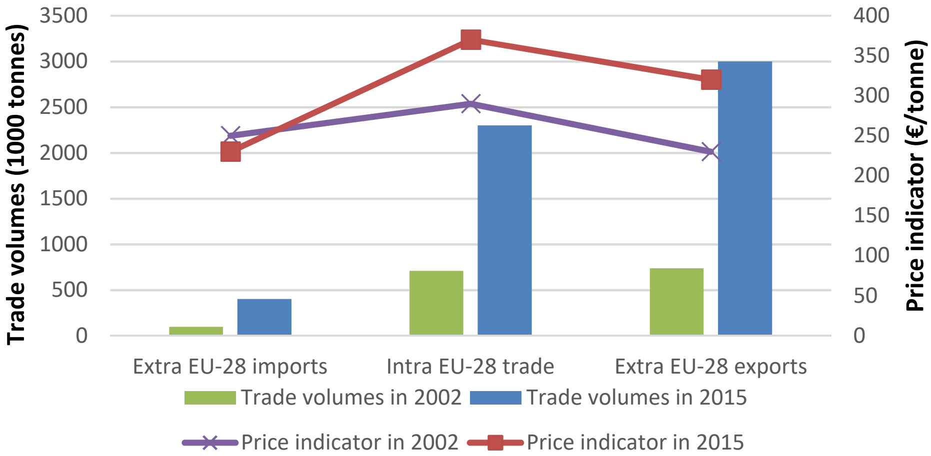

Figure 7. *Trade flows of waste plastics inside and outside EU. Value for Extra EU-28 export in 2015 and all price indicators are approximated from the source graphs (Eurostat, 2017)*

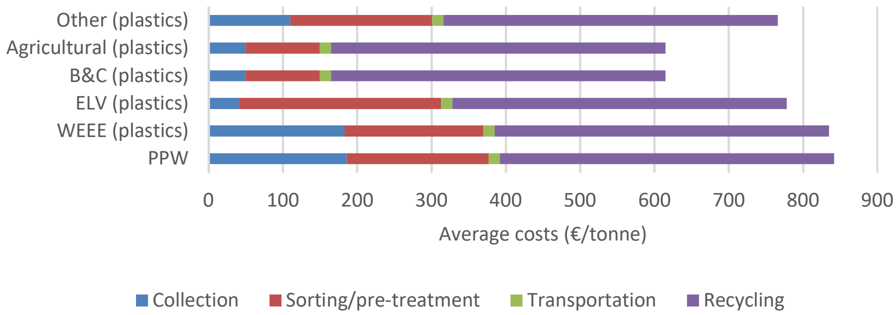

Figure 8. *Average cost of processes involved into recycling chain (Deloitte, 2015)*

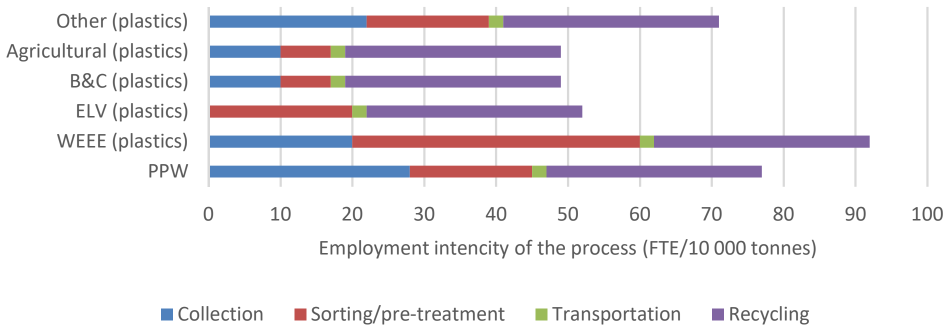

Figure 9. *Average amount of full-time employees required for steps in recycling chain (Deloitte, 2015)*

4.1.6. Environmental and social considerations

There are some additional considerations that drive the demand for the recycled material. The drawbacks of plastics use – energy-intensive traditional production process resulting in greenhouse gas emissions[16] and wide-spread plastic pollution[17] resulting from deficient end-of-life

[16] Around 1% of total global greenhouse gas emissions were produced by plastics production in 2012 (OECD, 2018)

[17] Extend end effects of the pollution are well-illustrated in the literature, for example read OECD report (OECD, 2018) or The New Plastic Economy Report by Ellen MacArthur Foundation.

waste management (OECD, 2018) are the other side of the plastic consumption coin. Nevertheless, the danger is the opportunity for those, who are willing to recycle. Below are some reasons why (OECD, 2018):

1. Plastic collection and its consequent recycling help to concentrate plastic environmental pollution, while continuing exploring the beneficial properties of plastics. Therefore, higher collection rates would reduce the diffusion of plastic pollution in the environment.
2. Both production of virgin plastics and incineration of them are carbon-intensive activities. Plastic recycling is a significantly smaller greenhouse gasses emitter than incineration or landfilling.
3. Production of virgin plastics requires more than 4-fold of energy required for production of secondary material

Recycling targets give the recycling industry a direction and have a strong environmental, social and economic impact. According to report by Deloitte, attaining the recycling targets presented in section 4.1.3, would result in annual savings of 8 Mt of greenhouse gas emissions and 50 000 direct and 75 000 indirect jobs created. Additional investment required to attain the targets is considered feasible and within a moderate range. For example, annual cost of increasing the processing capacity from the base level to the level required to attain recycling targets mentioned in table 7, would constitute around 1 billion € in 2020. That cost can be covered with ERP annual participation fee around 40 €/tonne, which is below the fee paid by Member States now. (Deloitte, 2015)

4.1.7. Barriers and drivers of plastic recycling

There are a number of barriers for increasing of plastic recycling and development of European recycling market (Deloitte, 2015; OECD, 2010; Deloitte, 2017; OECD, 2018):

- Insufficient European recycling capacity: despite being only 34% of the waste generated, already in 2012 the amount of waste sent for recycling was higher than installed recycling capacity in EU (Deloitte, 2015). Potential suppliers of recycled plastics do not invest in sorting and recycling capacity due to limited profitability of those (OECD, 2018)
- Insufficient demand for recycled plastics (Deloitte, 2015). Potential buyers use the recycled plastics rather limitedly due to uncertainty regarding their availability and quality. Many manufacturers use only virgin plastic as input due to its stability in terms of quality, performance and availability. (OECD, 2018)
- High levels of exports to non-EU countries, motivated by low labor cost (Deloitte, 2017). In 2012, around half of the waste plastic was sent outside EU (Deloitte, 2015). Recent ban of imports of plastic waste to China is expected to divert the significant part of exported waste to EU recyclers (Deloitte, 2017).
- Development of recycled plastic cost structure. The manufacturers of recycled plastics operate in the same market as virgin plastic producers and often the recycled plastics production is not economically competitive. Partially it can be attributed to cost structure of recycled material production and partially to prices of virgin materials, which might not include external cost[18] or might be affected by existing policies and traditions (OECD, 2018)
- Complexity of end-of-life products, which are difficult or costly to disassemble (OECD, 2018), increasing complexity of packaging (Deloitte, 2017)
- Low collection rates: for example, the collection rate for PPW in 2012 had to be increased from 41% of PPW generated to 70% of PPW generated by 2020 to attain 45% recycling target (Deloitte, 2015). In 2014 collection rate in EU-28 was 40% (Deloitte, 2017).
- Considerable collection and transportation costs of plastic wastes incurred by geographical dispersion
- Technical challenges associated with separation of plastic fraction from food, paper and other materials
- Uncertainty about presence of hazardous substances in the plastic waste
- Accountability and transparency in collection of data through the supply chain
- Inadequate and unharmonized monitoring of the flow and performance of plastics

[18] External costs are costs, associated, for example, with environmental burden.

- High landfilling rates and the absence of ban on landfilling

There are also a number of actions required and opportunities reported for stimulating demand and increasing the performance of recycling:

- According to 2018 EU Strategy for plastics in circular economy, by 2030 all plastic packaging should be recyclable (European Comission, 2018), i.e. possible to recycle. **Design for recyclability** guidelines strive to ensure that the new input material to the market is comparable with existing recycling system. If these guidelines are followed, a stream of products manufactured in accordance with such guidelines, when discarded, has a much better chance to be recycled into a high quality recyclate (Plastics Recyclers Europe, 2018). Manufacturers can use and retailers promote existing voluntary standards. Gradually the standards can become mandatory through EU regulations. EPR schemes could incorporate financial incentive systems on products designed for recyclability (Deloitte, 2017).
- **Known and communicated recycled content on the products.** While taxation and law reformation mechanisms could be required from the government, an industry could participate in development of recycled content standards to stimulate demand for recycled plastic containing products (OECD, 2018). Common labeling displaying percentage of recyclate in the product will then promote the use of higher recycled content containing products. Standardization organization can have a role in verification of the claim of recycled content (Deloitte, 2017). Green public procurement schemes and voluntary agreements in private sector can be used for commitment of a minimum recyclate content in the products (Deloitte, 2017)
- Demand can be stimulated by increasing **consumer and business awareness** on the environmental benefits of recycled plastics (OECD, 2018; Deloitte, 2017)
- The recycler could address the uncertainties associated with recycled plastic production by participating in creation of certification **standards** for recycling plastics, demanding and participating in **communication** across the plastic value chain and demanding of **restriction of hazardous chemicals** in manufacturing of plastic products (OECD, 2018). Communication platforms extending through supply chain can be build, based on existing initiatives (i.e. Dialogue Mechanism (Ellen MacArthur foundation, 2016)
- Capturing of quality waste can be implemented through increased number and quality of **separate collection schemes**. For example, deposit schemes are thought to be the most effective for collecting high quality and quantity of PPW (Deloitte, 2017)
- Sorting and recycling technologies can be developed through **co-funded effort** of manufacturers, recycling, sorting facilities and EU funds (Deloitte, 2017)
- Valuable material can be kept inside EU, supply stabilized and unnecessary environmental impact avoided through industry voluntary agreements, which can be developed to **prevent extra EU exports** with possibly gradual bans imposed later (Deloitte, 2017)
- Plastic **value chain** can be **re-organized**. For example, in a new configuration envisioned by McKinsey and Company, petrochemical and plastic companies are advancing the development of technologies for recycling, integrating the recycling units in the production sites and playing a central role in communication and recycling-friendly developments in the whole supply chain (Hundertmark, et al., 2018). Such shift is already taking place. A major polyolefin manufacturer, Borealis, acquired in 2016 two German plastic recycling companies (Borealis Media Release, 2016) and in 2018 another one (Borealis Media Release, 2018). Also, Lyondellbasell, one of the largest plastics, chemicals and refining companies in the world, in 2017 has partnered up with SUEZ, a leading player in the management of resources to jointly operate a high standard plastic recovery company located in Netherlands (Suez, 2017).

4.2. Safety and quality of waste materials

As was stated in section 3.1, for termination of waste status of a material, the EoW candidate should fulfil the technical requirements for the specific purposes and meet the existing legislation and standards applicable to products. Its use should also not lead to overall adverse environmental or human health impacts.

We will start this chapter with learning about indicators of quality change, which can be used during the plastic product life.

4.2.1. Indicators of quality during lifetime of a product

Plastics are very versatile group of materials. Generally, they have high strength or modulus to weight ratio, lack of conductivity and resistance to corrosion (F.Brinston & Brinston, 2008), but variation of properties within the group is significant. Classification of plastic materials can be based on main monomer of the polymer backbone and the side chains, chemical reaction involved into formation of the polymer, some property relevant for product manufacturing or design (like thermoplasticity or biodegradability), technical performance (commodity vs engineering grades) or converting process that plastic will be subjected to (Villanueva & Eder, 2014).

Factors influencing material properties of virgin materials and testing methods to evaluate these properties are resourcefully described in literature. What is relevant to the present work, if what causes the change in properties comparing to virgin material, how to asses and quantify those changes and how to demonstrate that the recycled material is safe and fulfills technical requirements for a specific application.

Compositional changes in plastic during its lifespan

To start, let's examine processes and materials involved in life of plastic packaging application, since packaging sector demands around 40% of all plastics. As we will later see, especially materials added during different stages of product life cycle will be important for our purposes.

At the beginning, a grade of plastic is designed for a conversion technology, i.e. film extrusion. During the plastic production, the polymer is supplemented with additives and possible additional components such as colorants or antistatic agents. The packaging design stage does not involve significant processing or volumes of materials consumed, but it has a significant effect on a quality of a secondary raw material (Plastics Recyclers Europe, 2018). During the plastic conversion processes such as cast or blown film extrusion, extrusion blow molding or injection molding, property-modifiers are used to further customize application specific properties. Order and structure of possible layers are designed together with use of special surface treatments and orientation of the plastic (Riley, 2012). Often, printing is involved in preparation of packaging for further use. Packaging conversion involves forming and gluing of packaging, filling and sealing of the product, labeling and attaching possible add-ons, packaging into retail and transportation packages and marking (Auvinen, 2018). Once the product is delivered, packaging is usually discarded, collected and in some cases recycled.

Resulting compositional complexity of waste can be illustrated by the scheme presented in table 9 (Thoden Van Velzen, 2015). Plastic is usually found in waste together with other materials. Some of the objects, found among plastic waste, can constitute a distinguishable stream. Plastic packaging is belonging to EPR scheme and is often collected separately, although in EU most often among other packaging (Deloitte, 2015). Plastic packaging stream consist of different types of packaging such as bottles, trays, films and laminates. Each component can further be broken down in one or few polymer types and other materials used such as adhesives and inks (Thoden Van Velzen, 2015).

Table 9. *Compositional complexity of waste stream (Thoden Van Velzen, 2015)*

Material level	Plastic		Paper & board	Metal	Organics
Object level	Packaging plastic (including moisture, dirt)		Non-packaging plastic		
Packaging level	Bottle		Tray	Film	Laminate
Component level	Body	Cap	Label	Glue	Ink

Change in composition of the waste stream continues also after products are discarded. Such processes as re-stabilization (Karlsson, 2004), decontamination (Palkopoulou, et al., 2016) and compatibilization (Karlsson, 2004; Luijsterburg & Goossens, 2014) are often constitute part of the recycling process. Also, contamination of input waste from shredding and cleaning process was reported (Eriksen, et al., 2018).

Change in concentration of organic substances during service life of plastics and more specifically of polyolefins was studied by Karlsson. According to her studies, hydrocarbons, carboxylic acids, ketones, alcohols, aldehyde, esters, fragrance and aroma compounds, amines and miscellaneous compounds were among low molecular weight (LMW) substances found in recycled polyolefins. The number of components was higher in recycled POs, than in virgin, but the types and amount of contamination was consistent. Aliphatic hydrocarbons were the major category of compounds identified in both virgin and recycled PE-HD. Also, ethylbenzene and xylenes were present in both materials, but in recycled one the concentration of those considered as hazardous aromatic hydrocarbons was about 5 times higher. The presence of aromatic hydrocarbons in virgin resins was explained by degradation of added substances during extraction and sample preparation techniques. Only recycled PE-HD contained carboxylic acids, some ketones and aroma and odour compounds, although concentrations of the former ones was low in comparison with aliphatic hydrocarbons. Additionally, recycled PE-HD contained esters used in cosmetics. Large number of branched alkanes and n-alkanes (C_{18}-C_{25}) and amines were found both in recycled and virgin PP; aforementioned aromatic hydrocarbons and esters used in cosmetics were found only in recycled PP and carboxylic acid and ketones were absent from both materials. (Karlsson, 2004).

Eriksen et al. compared concentration of metals in post-consumer household waste, mixed post-industrial and post-consumer industrial plastic waste, recyclates produced from those wastes and virgin plastics. Recycled samples from household waste had the highest overall metal concentration, higher than in recyclate from industrial wastes and unprocessed household wastes. In polyolefins, the highest average concentration in recyclate was concentration of Ti of order of 0.2 - 0.4%, while the concentration of other metals was below 0.05%. According to the conclusions of the research group, both polymer type and origin of the samples defined the differences in concentrations (Eriksen, et al., 2018).

In report by COWI and Danish Technical Institute (Hansen, et al., 2013), mapping of prioritized hazardous substances was made in polyolefins, among other plastics. The scope of survey was formulated plastic materials (i.e. manufactured polymer and product, such as packaging). According to survey, PE-LD and PE-LLD usually contain low level of added components and the only mentioned ones that may potentially contain hazardous substance are colorants and flame retardants in cable insulation. Components, potentially containing hazardous substances, mentioned for PE-HD are also only colorants and flame-retardants, used in cable applications and electronics in hot temperature applications. In addition, chromium oxide is mentioned as catalyst in some polymerisation methods. The components mentioned in the report for PP are antioxidants, colorants and flame-retardant in the same applications, as for PE-HD. (Hansen, et al., 2013)

Composition and processability as indicators of ability of recycled plastic to substitute a virgin one

Chemical changes in structure and morphology of polymer during processing, use and reprocessing of plastic can be summarized as change in molecular weight and molecular weight distribution, formation of short and long side branches and formation of new chemical bonds and new chemical groups (La Mantila, 1996; Karlsson, 2004). These changes can have a wide spectrum of effects on properties of recycled plastics, but the literature review reveals that researchers attribute the quality of recycled plastics and their ability to substitute a virgin one to the following properties:

- processability and particularly melt index of the recyclate (Järvelä & Järvelä, 2015; Karlsson, 2004).
- purity of sorted plastic waste (Hopewell, et al., 2009; Luijsterburg & Goossens, 2014) and purity of a recyclate in terms of foreign polymer (Karlsson, 2004)

- level and type of low molecular weight (LMW) organic substances (Karlsson, 2004) and metals in recyclates (Eriksen, et al., 2018)
- mechanical properties of a recyclate (Luijsterburg & Goossens, 2014)
- requirements of the applications for which the recyclate is used (Hopewell, et al., 2009)

For example, Järvelä & Järvelä discuss an importance of good processability of the recycled plastic, i.e. suitable viscosity for a chosen conversion techniques and stability of it during the processing (Järvelä & Järvelä, 2015).

Karlsson attributes the difference in mechanical properties and ageing resistance between recyclates and corresponding virgin plastics to contaminants such as inhomogeneities formed during service-life of plastics and non-polymeric impurities (Karlsson, 2004). Eriksen et al. refer in their work to “high quality” plastic, when describing a plastic such that its’ chemical composition and associated migration of potentially problematic substances allows it to comply with the strictest and most comprehensive legislation, such as food contact regulations (Eriksen, et al., 2018). Luijsterburg and Goosens state that recycled material quality can be assessed by analysis of mechanical performance and the composition and quote Karlsson to state that these are correlated. The authors themselves show with their work that more pure polyolefin waste fraction results in better mechanical properties of recyclates (Luijsterburg & Goossens, 2014).

Eriksen et al. compares the results of the compositional analysis of recyclates produced from household plastic wastes and industrial plastic wastes with available legal limit values and literature data and concludes that all-but one examined recyclate could be used in manufacturing of EEE or toys. For food contact applications, on contrary, they consider the recyclate analysed as possibly unsuitable (Eriksen, et al., 2018)

Effect of recycling process on the properties of recyclate

Selective or separate collection of waste material is often cited as a pre-requisite for a high quality recyclate. Suitable feed material in the nearest past was obtained through focusing the recycling schemes for post-consumer waste on packaging that is easy to identify and separate (such as PET bottles), while leaving multilayer or multicomponent structures outside recycling schemes (Hopewell, et al., 2009). According to Worrell, separate collection can guarantee a higher quality of the collected material, as the contamination with other materials is limited (Worrell, 2014). Nevertheless, Luijsterburg et al. states that for plastic packaging the collection scheme does not affect quality, but rather yield of the final product. Instead, extensive sorting, hot-washing step and centrifugation leads to more pure fractions and better mechanical properties of the recyclate (Luijsterburg & Goossens, 2014).

In research by Eriksen et al. the differences in metal concentration found in recycled material originated from collection method (i.e. source separated and sorted from commingled waste) were insignificant, neither food contact and non-food contact waste concentrations had significant difference (Eriksen, et al., 2018).

Oxidation of polymeric material results in formation of free radicals and eventually in formation of oxygen-containing structures such as carbonyls, alcohols, peroxides and olefinically unsaturated groups. Some of these structures have thermo-initiating or photosensitizing properties and, consequently, enhance the degradation rate of polymers, if present. Long-service life and aggressive environment of plastics results in increased concentration of such degradation-promoters and processing of a batch of plastics with varying degree of degradation results in diminished mechanical properties and increased susceptibility for degradation of a whole processed batch. (Karlsson, 2004)

Assessment of changes in properties of recyclate

Purity of the polyolefin recyclate or degree of separation of polyolefins can be measured by diffuse reflectance Near-InfraRed spectroscopy (NIR), Fourier Transform mid-infrared spectroscopy and Fourier Transform Raman spectroscopy coupled with multivariate data analysis

(Karlsson, 2004). In some studies, Differential Scanning Calorimetry (DSC) was used for compositional analysis of PE-HD/i-PP (Luijsterburg & Goossens, 2014) and for analysis of PE-LD/LLD blends (Wu, et al., 1991). Presence of products of degradation was found affecting the interpretation of the DSC curves. DSC of multiply extruded PE-HD was found to exhibit a bimodal melting peak, presumably due to presence of substances resulting from chain scissions (Karlsson, 2004).

Measuring techniques were found to affect PP content of a polyolefin recyclate. Measured by DSC or FT-IR, it was higher than obtained by NIR-sorting of a plastic waste stream. That was explained by presence of PP in multi-plastic products (i.e. bottles) and their sorting by dominant plastic by NIR. Also, PP content estimated by DSC was lower than estimated by FT-IR possibly due to higher migration of PP (as compared to PE) to the surface during compressional moulding of the samples. (Luijsterburg & Goossens, 2014)

For quantification of chemical substances present in plastics, traditional methods such as extraction coupled with high performance liquid chromatography (HPLC), gas chromatography (GC) or thin layers chromatography were used by Karlsson but was described by her as time and effort consuming. The researcher recommended ultraviolet and infrared spectroscopy methods (MIR with multivariable calibration, NIR in the diffuse reflectance mode) for rapid contamination quantification (Karlsson, 2004). Inductively coupled plasma mass spectrometry (ICP-MS) was used to quantify the metals concentration is samples of plastic waste and recyclates by Eriksen et al. (Eriksen, et al., 2018).

When exploring the methods to demonstrate the safety of the material derived from waste, the experience and expertise of the waste sector should not be forgotten. When the material is a waste, its' stability and safety for the environment is in focus, as the main objective of the waste legislation is to protect the environment and human health (EPC, 2008). Plenty of methods are used for characterization of waste, as data can be used to check the conformity to national regulations, to provide the basis for policy making or planning of facilities, and so on. Most commonly, material constituents of waste, particle size distribution, moisture content and density are analyzed. Chemical analysis of waste can commonly include organic and inorganic components, pH and calorific value. Additionally, performance characteristics such as compressibility of the mass, leaching and respiration test and biochemical methane potential are often tested from the waste (Lagerkvist, et al., 2010). Monitoring of cadmium, mercury and lead in emission from combustion of MSW is a normal practice (EEA, 2018; Sorum, et al., 1997).

4.2.2. Standards and documentation of quality

After examining material properties that scientists use for quality assessment of recyclates, let's continue with instruments of assessment, which industries use most often – standards.

Quality is defined by ISO 9000 as degree to which a set of inherent characteristics of an object fulfils requirements (ISO 9000, 2005). When plastic products are produced from virgin material, the material is thoroughly tested against a set of standards to define, whether the material and product made of it meets the requirements set by the application.

A standard is a technical document designed to be used as a rule, guideline or definition for repeatable undertaken. It is created in cooperation of regulators, manufacturers and consumers and results in increased safety and quality of products and economic benefits (CEN, 2018). In EU, the standards can be mentioned in both binding (Regulations, Directives and Commission Decisions) and non-binding (EU Communications, EU Green Papers, etc.) documents. Starting form 1985, EU has taken into use a so called "New Approach", according to which the essential requirements concerning the products are included into directives and the European Standard Organizations is given mandate to develop the standards in accordance with directive requirements. Using standards is voluntary, but it is usually the easiest way to show the compliance with regulatory requirements for the product. (SFS, 2018)

Specifications can be used to assess the suitability of the material as an input to the recycling process or to the plastic conversion process. In general, there are few types of available technical specifications that are related to waste plastic:

- based on standards and other general agreements for plastic waste or waste plastic used as input for mechanical recycling
- based on standards and other general agreements for recyclate used as input for plastic converting
- based on business-to-business agreements used to define quality of the traded material

Standards and B2B agreements for plastic waste

Specifications for plastic waste prior to reprocessing can be defined according to EN 15347 "*Plastic – Recycled plastic – Characterization of plastic wastes"*, which details mandatory and optional characteristics of plastic wastes needed to characterise a batch of material. One batch can be collected from a single source or contain a mixture of plastic types. It can be a quantity collected as it is or consist of material sorted by the collector. The batch is characterised by its size (weight of volume), colour, form of waste, and its history and composition. For composition the fractions of the main polymer and any other polymers in the waste should be stated, if known. Additionally, type of packaging in which the waste is collected should be stated. If the waste is homogeneous, the optional properties can be included in the characterization, such as mechanical properties of the main polymer, presence of impurities, etc. The supplier of the waste has an option to report the properties of the original polymer, if the waste was collected from a single source and is comprised from a single polymer type. Also, when properties have been measured from a representative sample from a batch, that should be stated (SFS EN 15347, 2007).

Within German Duales System Deutschland (DSD) the plastic packaging waste after sorting is equipped with a label stating a specific fraction (i.e. Plastic film No 310, PP No324, etc). The specifications for these fractions include description of the material allowed (i.e. films larger than A4 including labels), purity of the sorted fraction as determined by sampling and subsequent analysis and maximum content and type of allowed impurities. The example of a specification of a plastic film fraction is presented in the appendix A. (Villanueva & Eder, 2014)

Standard EN 15347 might provide waste suppliers or collecting/pre-treatment facility with a backbone for characterisation of the plastic waste. For packaging, specifications, such as those issued by DSD, provide packaging waste suppliers with instructions on allowable materials and their content in the waste. Within DSD system, one further step is taken towards controlling the quality of input material to the recycling system by offering packagers producers certification of recyclability for their products (Institute cyclos - HTP, 2017; DerGrunePunkt, 2017).

Standards and B2B agreements for recyclate

Specifications for recycled PE plastics can be defined according to European standard EN 15344:2007 "*Plastics. Recycled Plastics. Characterisation of Polyethylene (PE) recyclates"*. According to that standard, each batch of the recycled PE material[19] should be characterized with set of required or optional characteristics. Required properties for material characterisation are bulk density, colour, particle size, Melt Flow Rate (MFR) and shape. Contamination can be optionally tested by investigating a piece of non-filtered extruded film with a magnifying glass and counting non-melted particles and visible impurities of size 100 microns or larger. Other suggested optional tests include moisture and ash content determination and determination of mechanical properties (SFS-EN 15344, 2007).

[19] The following constituents are included into composition of the recycled PE material (SFS-EN 15344, 2007): "polymeric matrix, consisting of polyethylene (PE content; fillers, pigments and additives; impurities or contamination in a quantity which do not compromise the workability characteristics of recycled PE; polymers compatible with the polymeric matrix" (SFS-EN 15344, 2007)

Interesting observations can be made by comparing standards for designation of virgin and recycled materials. For designation of virgin PE, ISO 17855 -1:2014 "*Polyethylene (PE) moulding and extrusion materials - Part 1: Designation system and basis for specifications"* can be used. That standard introduces a system of designation of PE, which can be used as a basis for classification of PE. According to that standard, PE can be described with five data blocks containing identification symbol (block 1), content and presence of filler or/and reinforcing material (block 2), intended method of processing or/and primary application and important properties and presence of colorants or other property-modifiers (block 3) and density and melt mass-flow rate (block 4). Additional information can be stated within block 5 (SFS-EN ISO 17855-1, 2014).

The author did not find a similar standard for "pure" PE recyclate, but concluded that ISO 18263- 1:2015 standard "*Plastics - Mixtures of polypropylene (PP) and polyethylene (PE) recyclate derived from PP and PE used for flexible and rigid consumer packaging- Part 1: Designation system and basis for specifications*" can be used for comparison. That part of the standard describes a set of properties, which can be used as a basis for specifications for mixtures of PE and PP recyclate. According to it, the types of mixtures of PE and PP recyclate can be differentiated from each other by classification based on 5 data blocks: composition (expressed by a code-letter, block 1), form and color (block 2) and density and melt mass-flow rate (block 4). Block 3 is not used and block 5 can be used for a supplementary information (ISO 18263-1, 2015)

Despite an appreciable attempt to standardize the way the information is presented for virgin and waste-derived materials, some significant pieces of information such as application and intended processing method are not included in the designation of PE/PP mix. Also naming of the standards are different –the virgin material standard includes "molding and extrusion" already in the name of the standard, while for PE/PP recyclate mix the same destination is stated only in the text of the document.

Standard 18263 – 1:2015 does not include any information regarding expected properties and performance of the virgin and recycled materials. Instead, the text states that similarly designated materials do not necessarily have the same performance. The properties of the PE/PP recyclate mix are addressed in the second part of aforementioned ISO 18263 standard. Additionally to the regular material properties such as tensile properties, impact strength and MFR, the standard presents the properties that are commonly used or considered important for characterization of the recyclate mix. These properties are PP/PE composition by mass, density, color and form (such as granules or flake). The ratio of PP/PE should be determined according to traceable documents from the supplier, although it is noted in the text that it is known that ratio in question can be determined by FTIR spectrometer. Also, the relationship between the composition of the mix and tensile properties and morphology is shown in the appendix B of the standard. (ISO 18236-2, 2015)

Specifications related to virgin polyolefins

Compliance with EoW pre-requisites can be indicated by compliance with established relevant technical specifications or technical standards that are used for virgin materials for the same purpose (European Comission, 2012).

Technical specifications related to safety of virgin materials can be established by examining compliance statements, issued by the manufacturers of the virgin material. Compliance statements declare compliance to food contact regulations and other chemical and product regulations and can include detailed list of the substances not incorporated in the material (Borealis, 2018). If, on the other hand, material exhibits hazardous properties, material Safety Data Sheet (SDS) is produced for it (ECHA, 2012).

Some product standards describe the possibility to use production residues and recycled plastic on the side of the virgin material. According to EN 1852 "*Plastics piping systems for non-pressure underground drainage and sewerage. Polypropylene (PP). Part 1: Specifications for pipes, fittings and the system",* in non-pressure pipes own production residues conforming to that standard can be used without limitations additionally to virgin PP. Also, external reprocessed and recycled material from pipes and fittings can be used, if it is produced under EU or national standards and satisfy conditions for products produced from virgin material and some additional conditions. Material originating from other than pipes and fittings products cannot be used (SFS-EN 1852-1:2018, 2018). Use of recycled material is similarly limited/allowed in EN 13476-3:2018 "*Plastics piping system for non-pressure underground drainage and sewage – Structured-wall piping systems of PVC-U, PP and PE – Part 3 […]*". Additionally, the standard allows up to 5% by mass of external reprocessed material from PE rotational-moulded fittings and other components covered by an agreed specification (SFS-EN 13476-3:2018, 2018).

The external recycled material from pipes and fittings is expected to meet all requirements for virgin material used for the same applications and additionally the following: (SFS-EN 13476-3:2018, 2018):

- requirements for density, thermal stability (OIT), MFR, ash residue, volatile content and extraneous polymer content are quantitatively defined, and test methods specified
- presence of impurities is to be included in the specification; mesh size for filtering the impurities is to be agreed on between supplier and manufacturer
- property-modifiers and/or pigments included in the external reprocessed material are to be analysed and their presence agreed on between supplier and manufacturer
- each delivery should include a declaration of conformity to the agreed specifications
- the quality plan of the supplier should conform to ISO 9001

It is also stipulated by the standard that the samples for analysis of the recycled material should be taken from each individual material batch source, unless the source of material is consistent. Pipes, fittings and other products produced under a quality mark are considered to be a consistent source (SFS-EN 13476-3:2018, 2018).

Compliance statements, SDS and product standards can be used not only to evaluate suitability of recycled material for a specific application, but also for evaluating the composition of the input material for the reprocessing. Additionally, product design guidelines can be used for that purpose. Plastic Recyclers Europe have created an online tool "RecyClass", which can be supplemented by an optional certification, defining the recyclability of a single package on a scale from A (easy to recycle) to F (incineration is the only feasible option). Using RecyClass tool, designer of the package can already at the design stage evaluate the recyclability of the package (Plastics Recyclers Europe, 2018). For example, PE transparent flexible film is whether acceptable to PE recycling system or pose a high risk of interfering with it, depending on its main plastic type, colour of the packaging, plastic type of used barrier layer, property-modifiers, materials used in labels, types of adhesives and inks used and area of packaging covered by printing (Plastic Recyclers Europe, 2017). In Finland, a "Guide for plastic packaging suitable for recycling" is available (Suomen Uusiomuovi Oy, 2018).

Environmental considerations in standards

So far, the reviewed standards related to waste, recyclate and products made with recyclate were mostly concerned with designation, appearance and technical performance of the material. CEN technical report (TR) 15353 "*Plastics. Recycled plastics. Guidelines for the development of standards for recycled plastics*" provides a backbone for drafting of standards for recycled plastics. According to CEN/TR 15353, all standards should incorporate considerations of environmental aspects, which should mainly concentrate on reprocessing stage, as all other stages of recyclates life are expected to have similar environmental impact as virgin plastics. Environmental aspects include use of resources, energy consumption, emissions to air and water, impact on soil, waste produced, migration of dangerous substance and accidental risk to environment. The standard also describes the common for all recycled plastics general conclusions, reached related to mentioned aspects. These conclusions include the remarks that the recycling of waste consumes less energy than equivalent production of virgin polymer and that recycling processes are subject to national regulations and therefore all the emissions are strictly controlled. (CEN/TR 15353, 2007)

4.2.3. Regulations related to waste plastics

Wastes can be associated with risks to health or environment. In order to minimize these risks, the waste producer or holder should stay responsible for the waste, until it has undergone recovery (European Comission, 2012). After the material ceases to be waste, it becomes non-waste and therefore falls under jurisdiction of chemical and product related legislation (EPC, 2018). The reprocessed material should have waste status only if it should be controlled under waste legislation to protect environment and human health (Villanueva & Eder, 2014)

For termination of waste status, the material should be proven to be safe for health and environment. For compliance with this, the use of the material under the relevant product legislation and the use of the same material under waste legislation can be compared. The relevant questions to answer are “Is the product legislation sufficient to adequately minimise the environmental or human health impacts? Would releasing the material from the waste regime lead to higher environmental or health risks?” (Kauppila, et al., 2018; European Comission, 2012).

Composition, and particularly presence of contaminants in recycled plastics play an important role in performance of the recyclate and in its ability to substitute a virgin material in a safe for health and environment way. In reviewed standards for plastic waste and recycled plastics, the presence of contamination is considered mainly in terms of undesired polymers or other materials such as paper and metal. The presence of contamination is evaluated based on visual examination of the melt (EN 15344), composition of the melt (ISO 18263) or expected to be absent due to prohibited input waste material to the process (ISO 18263, industry specifications). Product-related standards mention the need for characterisation of material on presence of property-modifiers and quantification of extraneous polymer (EN 13476).

Standards reviewed alone might not provide the recycler with all necessary means to demonstrate the compliance with conditions for re-classification of waste as non-waste. In order to observe the gaps, some relevant for the recycler product regulation is reviewed below. The review follows the presentation by other authors (Eskelinen, et al., 2016; Kauppila, et al., 2018) and is supplemented with details from the regulatory documents.

Input material for the recycling operation is waste, therefore such operations as handling, storing or transporting of the input material are directed by waste legislation. The recycler of the waste should be aware that if it contains any substances listed in Annex IV of the so-called POP Directive, the recycling of that input is mainly prohibited (EPC, 2004).

In principle, all chemical substances as themselves or in mixtures or articles are subject to REACH and CLP Regulations (ECHA, continiously updated). REACH Regulation strives to ensure the high level of protection of human health and environment, free circulation of substances on the internal EU market and improved the competitiveness of EU chemical industry (Eskelinen, et al., 2016). CLP regulation provides the basis for identification, labeling and packaging of substances and mixtures in line with Globally Harmonized System (GHS) and for safety-data sheets (SDS) preparation. Requirements under REACH and CLP are discussed in detail at the end of this section.

Producer of material for construction should consider Regulation (EU) No 305/2011, which describes the marking of construction products and pre-requisites for CE-marking on them (Korpivaara, et al., 2013).

If the recycled material is to be used in EEE, it should satisfy the requirements set by RoHS Directive, which limits use of certain substances in EEE equipment placed on the market. The substances which use is restricted are lead (0.1%), mercury (0.1%), cadmium (0.01%), hexavalent chromium (0.1%) polybrominated bisphenyls (PBB, 0.1%) and polybrominated diphenyl ethers (PBDE, 0.1%). The number in the bracket indicates the maximum concentration values tolerated by weigh in homogeneous materials (EPC, 2011). The same directive also describes the applications, in which the aforementioned restrictions do not apply.

If the recycled material is to be used in manufacturing of car parts, it should not contain lead, mercury, cadmium or hexavalent chromium and otherwise satisfy the requirements specified in ELV Directive (EPC, 2000).

If recycled material is to be used for packaging, the manufacturer has to be aware of requirements of Directive 94/62/EC, according to which the sum of concentration levels of lead (Pb), cadmium (Cd), mercury (Hg) and hexavalent chromium (Cr (VI)) in packaging should not exceed 100 ppm (EPC, 2015).

One of the ultimate quality tests for the recycled plastic would be its use in applications intended to come in contact with food. If plastic is to be used for production of food contact applications, it should satisfy general requirement for all food contact materials described in Framework regulation EC 1935/2004 and be manufactured according to good manufacturing practices described in Regulation EC 2023/2006. A consolidated Regulation EU 10/2011 includes a list of authorized substances for the manufacturing of plastic food contact materials, sets an overall migration limit and defines specific migration limits (SMLs) for individual authorized substances. In case a recycled plastic is to be used for manufacture of materials and articles in contact with food, the manufacturing process should be also assessed by ESFA and authorized by European Commission according to requirements established by EC 282/2008 Regulation (ESFA, 2015).

The mentioned requirements encircle requirements for input material, recycling process, characterization of the recycled output and establishing conditions of use. Plastic input used for the process should either originate from a closed and controlled product loop or should undergo a challenge test or any other test capable to demonstrate that the recycling process reduces the level of contamination to the safe for health level (European Comission, 2008).

Rather than addressing presence of polymeric contamination, the regulation 282/2008 addresses contaminants of concern, i.e. those contaminants that are present in the articles manufactured from the recycled material (i.e. have survived potentially few thermal cycles) and can migrate into foodstuffs above the safe agreed levels (Palkopoulou, et al., 2016). The compounds that can potentially migrate into content from the packaging made of recycled material can originate from non-intended content of the packaging during its post-production life, non-food contact polymer contamination present due to insufficiently efficient sorting process or recycling process itself. Examples of such compounds are chemicals used in the washing and degradation products of the polymers. Some of these compounds might be eliminated during the recycling process, for example by washing or evaporation. Some of the compounds might eventually migrate in the food content in unsafe for human amounts. Behavior of the compounds is related to their chemical and physical properties, mainly polarity and molecular weight. In risk assessment performed by ESFA the input material, efficiency of the recycling process in removing of contamination and intended use are assessed (ESFA, 2008).

Requirements under REACH and CLP

There are at least three requirements that might concern the recycler under REACH and CLP regulations (Ökopol Institute, 2012):

- The registration requirement
- The information requirement
- The communication requirement

Additionally, the recycler should fulfill the downstream user obligations under REACH, in case he/she uses the virgin materials in the recycling process (for example, extra property-modifiers) (Ökopol Institute, 2012).

Regarding **registration**, the substance that has ceased to be waste under conditions described in WFD is referred to as “recovered substance” under REACH. As any other substance that fall under scope of REACH, recovered substance is, in principle, a subject to REACH regulation (ECHA, 2010).

However, the registration requirement does not apply, if the same constituents of the recycled polymer has been already registered and information regarding registered substances is available to the company. The registration of the constituents could have been done in the same supply chain in the different supply chains (ECHA, 2012). The constituents of a polymer rather than polymer itself should be registered, as under REACH registration requirements concerns not the polymers, but their chemically bound constituents (Ökopol Institute, 2012)

Polymers are not required to be registered, as they are generally considered to be safe for the public[20] (ECHA, 2012). According to Article 2 (9) of REACH, provisions of titles II ("Registration of substances") and VI ("Evaluation") do not apply to polymers (EPC, 2006).

Guidelines by ECHA on polymers and monomers explains that generally, (virgin) polymer manufacturer will not have to register monomers or any other substance chemically bound to the polymer either, as they would be already registered by the previous actor in the supply chain. Nevertheless, if (virgin) polymer consists of 2 w% or more of monomer or any other substance that was not previously registered and total quantity of such substance chemically bound to the polymer makes up 1 tonne or more per year, the manufacturer or importer of a (virgin) polymer should submit a registration for the monomer or any other substance used (ECHA, 2012).

Additionally to monomers, the (virgin) polymer includes stabilizers and impurities. Stabilizers are additives required to preserve the stability during the manufacturing. Under REACH, only in-manufacturing-used stabilizers are referred to as "additives". Impurities are unintended constituents of the polymer. They and stabilizers are considered to be a part of the polymer and do not require additional registration. All other additives are not referred to as additives in the text of REACH or guiding documentation. When (virgin) polymer contains such non-during-manufacturing stabilizing additives, the (virgin) polymer should be considered a mixture or an article, for which normal registration procedure would apply (ECHA, 2012).

Let's now analyze the situation with recovered polymer: it might contain another polymer(s), non-stabilizing additives and impurities. Can it be considered the same as similar virgin polymer and be exempt from registration?

To answer that question, the recovery operator has to establish whether the recovered substance is a substance as such, a mixture or an article. Substances can be further divided into well-defined mono- or multi –constituent substances or UVCB[21] substance. Detailed guidelines on establishing type of the substance are available from ECHA (ECHA, 2017). For example, when it is not possible to scientifically define whether the substance is a polymer or not and/or concentration and chemical structure of monomer in the substance, the substance should be regarded as UVCB substance and registered accordingly (ECHA, 2012). UVCB and multi-constituent substances cannot usually be exempt from registration (Ökopol Institute, 2012) and therefore would require more detailed evaluation, which is outside the scope of the present text.

If the recovered substance contains ≥ 80% of one main constituent, it is usually a substance, and several constituents with fraction of each ≥ 20 w% are a mixture (Ökopol Institute, 2012). If the substance contains some constituents that have being intentionally added originally (i.e. fillers, colorants, etc.), but don't have any function in the recovered substance, such constituents should be regarded as impurities, if the content of such constituents is below 20 w%. If a certain constituent in the recovered substance is sought after (i.e. specific property-modifier), it should be considered as separate substance and not as impurity even at concentrations less than 20

[20] Polymers might be, nevertheless, subject to requirement for provision of information, authorization and restriction (ECHA, 2012)

[21] Substance of **U**nknown or **V**ariable composition, **C**omplex reaction products or **B**iological materials

w%. (ECHA, 2010) Substances with deliberately recycled impurities should be considered a mixtures (Ökopol Institute, 2012) In a mixture each substance identified can contain impurities (ECHA, 2010).

For recovered polymer which is a well-defined substance, the identity of the main constituent defines sameness. Literature states that names or/and composition of the main constituents should be the same (Ökopol Institute, 2012; ECHA, continiously updated). According to ECHA guidelines, information listed in section 2 “identification of the substance” of Annex VI to REACH should be available in order to identify the substance. At least name or other identifier (IUPAC nomenclature, CAS number), information related to molecular and structural formula of each substance and composition are required for identification. If production of such analytical data is impossible, other information for identification should be provided and justified. (ECHA, 2010; ECHA, 2017). For mixtures the sameness should be checked for all the constituents (ECHA, 2010)

Previous registration can be checked through SIEFs, through dissemination website by ECHA or own channels of the manufacturer. The recovery operator willing to benefit from exemption from the requirements to register the recovered substance should be able to provide on request the relevant documentation, justifying that the recovered substance qualifies for exemption (ECHA, 2010).

The second obligation under REACH and CLP is **information requirement**, according to which the recovered substance has to be classified and labeled sufficiently to provide information for the users. The provision of information requires the identification of hazardous profile of the substance recovered. (Ökopol Institute, 2012)

As most monomers are present in the polymer only in trace amounts, the hazardous profile of the recovered polymer will be mostly determined by the type and amount of the substances added and by impurities present. While for registration requirement 20 w% threshold was sufficient to evaluate the need for re-registration, the existence in mix of constituents present at as low as 0.1% concentration might have to be acknowledged for identification of hazardous profile (Ökopol Institute, 2012).

Even though both hazardous waste and hazardous chemical are regulated by EU, discrepancies exist in the chemicals and waste classification as hazardous (European Comission, 2018). While recent guidelines on waste classification as hazardous can be used for waste (EC, 2018), CLP regulation should be used as the basis for classification of chemicals, including recovered substances (Ökopol Institute, 2012).

The information regarding the composition of the recovered substance can be obtained either through complete laboratory analysis of the constituents or by accessing the available knowledge related to composition. There are two routes suggested in the literature for obtaining the required information related to composition:

First strategy is analysis of data containing “positive knowledge” that the problematic substance is not present in incoming waste supplemented by documented quality assurance procedures. Data sources containing such “positive knowledge” can include SDS obtained from polymer manufacturer, product specifications for products included in the waste stream, regulations related to a specific waste stream (i.e. food contact materials). Quality assurance procedures should include incoming and outgoing material checks, separation of waste stream with known constituents from the rest, process control and documentation of the process. (Ökopol Institute, 2012)

The second strategy is obtaining the information that the problematic substance is present in the incoming waste stream and follow-up procedures necessary to evaluate the composition of the output material (Ökopol Institute, 2012).

The last obligation of the recycler discussed within the present text is **communication requirement.** If according to hazardous profile established for the substance recovered, the substance is dangerous or subject to restrictions, the SDS should be provided to the recipient of the recovered substance. The recovery operator should check whether the information available on the registered substance is relevant and sufficient for the recovered substance and its possible uses. In case the hazard profile of the recovered substance differs from the registered one, that change should be described and communicated to the downstream user. The recovery operator should also assess, whether the exposure scenarios of the registered substance cover all the expected uses of the recovered substance (ECHA, 2010).

In order to assist the recovery operators, Polymer Comply Europe has developed an SDS-R tool, which provides a recycler, upon a fee, with a generic or tailor-made SDS, based on industrial knowledge and scientific assessment (PCE, 2018).

The following sources of information are recommended by ECHA for establishing the detailed composition of a recovered substance, if the need for additional safety information arises (ECHA, 2010):

- representative chemical analysis of the waste and recovery stream (the same information can be possibly derived from the literature)
- efficient communication with suppliers of the already registered substance or original producers of the to-be-waste product
- quality classes of secondary raw material
- documentation related to compliance with EoW criteria

According to the guidelines, a case by case analytical assessment of recovered material need only be carried, if collecting sufficient information from all other sources fails (ECHA, 2010).

Regulatory bodies acknowledge that information availability on presence of substance of concern is poor and feasibility study was promised to be launched in 2018 on use of information systems and tracing technologies that would improve the information flow (European Comission, 2018)

If the recycled polymer is not expected to exhibit any hazardous properties within designed application, the recycler should be able to demonstrate why exposure is not to be expected. Practice of voluntarily SDSs is common for substances that do not require mandatory SDSs (Ökopol Institute, 2012).

4.2.4. Quality and safety assurance and declaration

Standard EN 15343 “*Plastics recycling traceability and assessment of conformity and recycled content*“ is developed according to guidance by European Committee for Standardization (CEN) on development of standards for recycled plastics. The standard prescribes the necessary procedures required from products produced fully or partially from recycled plastic, if proof of traceability is requested by legislation, standards or end users.

The standard states that quality of the recycled product is determined by the controls of the input material, of the recycling process and of the material produced. Controls of the input material include design of the sorting and collecting process. Traceability requirements include identification of each batch according to EN 15347 and record keeping by sorters and collectors. Further, the standard requires control of the processing. The methods of processing control include recording the process variables, testing the output for quality control purposes and identifying each batch of the output. For some applications, a challenge test might be required. Characterization of the material produced should be performed according to standards, mentioned in section 4.2.2. At last, the standard prescribes the supplier of the recyclate to collect relevant documentation on each step of the recycling process and to appropriately document and record all procedures of collecting and recording of the data. (SFS-EN 15343, 2007)

Earlier mentioned EN 15344 standard prescribes the supplier to maintain records of the quality control carried out during processing, checks of incoming materials and finished products. It also states, that the documentary evidence might be required to back up the recycled content or to describe the previous history of the material. The standard specifies that system certified to EN ISO 9001 would be sufficient for quality assurance (SFS-EN 15344, 2007). According to another earlier mentioned CEN/TR 15353 standard, the lack of product history can be accounted for with tighter and more frequent process control and/or recycling process certification (CEN/TR 15353, 2007).

Recently (last update February 2018), a European-wide certification aimed at post-consumer plastic recyclers has being developed. Voluntary certification EuCertPlast is based on EN 15343:2007 and its aim is to recognize plastic recyclers operating at high standards. To become a certified recycler, the recycler should choose an accredited EuCertPlast auditor, who would inspect the recycling plant. After collection and processing of all the relevant information, the third-party checks uniformity and rigorousness in all reports. Once conformity to all requirements is ensured, the auditor issues 1-year valid certification (EuCerPlast, 2018).

Claim of recycled content and CE-marking

Downstream user of a recyclate can declare the presence of the recycled content in its product and visualize it with a symbol such as Mobius loop (see figure 10).

Figure 10. *Mobius loop that can be used for visualizing the claim regarding the recycled content (ISO 14021:2016, 2016)*

The statements that the product has recycled content is self-declared environmental claims. This claim should be verifiable, and the claimer is responsible for provision and evaluation of data required for verification. The evaluation should be retained for the lifetime of the product and be public or disclosable upon request at administrative cost. Methods used for evaluation of the claim should be described in some recognized standards or peer-reviewed trade or industrial methods or available for peer-review. (ISO 14021:2016, 2016)

Further, according to ISO 14021 standard, only pre- and post-consumer material can be calculated in recycled content. Referring to definitions of pre-consumer (post-industrial) material in section 2.2 and non-waste in 2.6, the part of post-industrial residues that can be immediately absorbed back into manufacturing process cannot be calculated as recycled content.

Full circularity should eventually mean incorporation of the recyclate into products on the side of the virgin material. Safety of virgin materials is extensively monitored and communicated to consumers. One common way for product manufacturer to communicate compliance with legislation is CE Marking, which literally means “European Conformity”. It signifies that the product sold in the European Economic Area (EEA) complies with safety, health and environmental protection requirements (European Comission, 2018). However, compliance with CE marking alone is not sufficient for termination of waste status of the material, as CE marking does not cover environmental qualification in terms of hazardous substances (Salminen, 2018).

5. CASE STUDIES: FINNISH POLYOLEFINS

Chapter 5 presents two case studies, which were performed with purpose of collecting and presenting in one place information necessary for waste status termination application. In the first case study EoW candidates were recovered from flexible plastic packaging stream, originating from post-consumer industrial/commercial waste and in the second – from plastic pipes, originating from post-consumer C&D waste. The chapter starts with an overview of Finnish recycling market. In chapters 5.1 and 5.2 relevant waste streams are described and methods, used for analysis are presented. Chapter 6 then presents the actual analysis of the streams and an example of application for termination of waste status.

Plastic consumption profile in Finland and Europe are similar. In Finland, as well as in Europe, plastics are mainly used by packaging (40% in 2005) and construction (24% in 2005) industries. The rest is demanded by production of electric and electronic devices (6%), agriculture (6%) and other production (21%). Differently from Europe, production of vehicles consumes only 3% of plastic converters demand. (Eskelinen, et al., 2016)

In Europe generated plastic waste constitutes around half of the total amount of plastics used (Salmenperä, et al., 2015; Villanueva, et al., 2010). In Finland around 600 kt of plastics are used annually for production of plastic products (Muoviteollisyys ry, 2018; Sahimaa & Dahlbo, 2017). Using predictions based on different development scenarios, Salmenperä et al. have estimated that in 2020, the amount of plastic waste in Finland will be 365-380 kt and in 2030 – 407-447 kt (Salmenperä, et al., 2015).

Sahimaa and Dahlbo has estimated that annually 117-158 kt of plastic packaging waste and 68 – 122 kt of plastic from C&D waste were generated in 2013 in Finland (Sahimaa & Dahlbo, 2017). Estimation of Eskelinen et al. for plastics from construction waste for year 2012 ranged from around 20 kt to around 220 (Eskelinen, et al., 2016).

Separately collected plastic packaging and plastics from households, agricultural films, plastic waste from C&D activities, industrial and commercial separately collected plastic waste, plastics from mechanical separation processes and production residues of plastic industry are processed by Finnish recycling industry (YTP liitto, 2017; Merikarvia-lehti, 2017).

Re-granulate is sold to industries and converted into bags, waste water pipes, flower pots and buckets (Yle, 2018). Examples of plastic industry companies using re-granulate as raw material are Amerplast Oy and Orthex Group. Amerplast Oy produces grocery bags containing more than 95% of recycled material (Amerplast, 2018), from which minimum 45% are originated from post-consumer plastic packaging and the rest – from commercial, industrial, agricultural waste plastics and company's own internal scrap (Essi kiertokassi, 2018). Such bags have similar functional properties as the bags from virgin plastic, but printability and visual appearance might not be as good (Suomen Uusiomuovi Oy, 2018). Orthex Group produces flower pots, buckets, containers and storage bins that consist of 100% recycled plastic. In 2017 the company has announced intentions to use the recycled plastics in 20 products of their offer (Orthex group, 2017). According to Fortum Waste Solution Oy, in Finland 70% of collected plastic packaging from households are recycled – 40% into pellets for plastic industry and 30% into plastic articles such as CIRCO profiles and other industrial applications (Fortum, 2018).

5.1. Post-consumer industrial/commercial flexible plastic packaging

In Finland, plastic waste produced by industry and commerce can be divided into two relevant for recycling groups: post-industrial production residues of plastic industry and post-consumer industrial wastes produced by other industries and commerce. Post-consumer waste is mostly produced in connection with unwrapping of goods and production of plastic packaging. (Järvinen & Saarinen, 2016)

Source separation is pre-requisite for recycling of plastic waste of industry and commerce. Source-separated production residue of plastic industry is often well-marked and sorted into plastic types or even sub-types. That kind of knowledge necessary for separation might not be available for all industrial collectors and commerce. As a result, collected and source-separated plastic waste collected by these actors is more heterogeneous. Most commonly collected and source separated post-consumer industrial/commercial plastic waste is stretch- and shrink plastic wrap, made mostly of PE-LD or PE-LLD. It is often baled at collection point. Waste collected in this way is often transparent, but contains labels, what complicated the further processing. (Järvinen & Saarinen, 2016)

Collection of post-consumer waste originating from commerce is based on agreements with waste collecting companies. Järvinen & Saarinen have estimated that 40 kt of plastic waste were generated by other-than-plastic industries and commerce in 2016. Of that amount, around 22% are source-separated and collected PE-LD and PE-LLD plastics; around 9% are other source-separated plastic. The rest, or around 69% of industry/commerce plastic waste generated, is collected as a part of energy or mixed waste destined for energy recovery. The numbers presented are derived from a pie-chart "*Estimation of non-plastic industry and commercial plastic waste management*" in the source literature (Järvinen & Saarinen, 2016, p. 67).

In Finland, the producer responsibility for packaging encompasses packers of the products and importers of the packaged products, whose turnover is at least 1 M€ (Järvinen & Saarinen, 2016). According to producer/importer organization, in 2015 in Finland, 116.5 kt of plastic packaging was placed to market and equal amount of waste was produced (Pirkanmaan ELY-keskus, 2017). From that amount 27.6 kt (24%) was recovered as material (Pirkanmaan ELY-keskus, 2017). Uusimaa magazine refers to Muoviteollisuus Ry, Palpa Oy and Suomen Uusiomuovi Oy to report that of 123 kt of plastic packaging was produced in 2017. From that amount, almost 72 kt was consumer packaging, of which 10% were recycled; 37.5 kt were industrial packaging with 36% recycled and 13.5 kt were refundable plastic bottles, of which 91% was recycled (Vanninen, 2018).

The share of industrial packaging reported is in line with shares presented in report by Finnish Ministry of Employment and the Economy. According to it, roughly 30% of plastic packaging waste is originating from industry, commerce, primary production or institutions, while around 70% are considered consumer plastic packaging waste. Consumer plastic packaging is considered to be plastic packaging from households, hotels and restaurants and PET bottles (Merta, et al., 2012). The same report references Kaila et al., who estimates that around 10% packaging amounts in general (not only plastics) is excluded from statistics for various reasons and provides an overview on statistical uncertainties related to plastic packaging amounts reported (Merta, et al., 2012).

In Finland no national standards for recycled plastic or plastic waste exist, but the specifications of separately collected post-consumer industrial plastic waste can be constructed based on instructions available at industrial packaging collection terminals. According to these instructions, packaging waste brought to the collection facilities should be source separated by plastic type, clean and dry. Protective packaging films, plastic bags and wraps, expanded polystyrene packaging, canisters and crates are examples of products mentioned in the instructions. Dirty and containing hazardous waste packaging, PVC packaging, household packaging, packaging production residues and non-packaging, such as agricultural films, were not allowed. Compliance with the requirements would be checked by the collection facility (Suomen Uusiomuovi Oy, 2015)

Generally, nonfood packaging can include industrial liners, shipping sacks, bubble packaging, stretch wrap or shrink wrap (APC, 1997), but as we know by now, post-consumer industrial plastic waste produced in Finland is mainly constituted of stretch wrap. Stretch wrap is used to unitize goods for transporting. Once it is stretched – by hand of a machine – it clings to itself. Stretch wrap can be manufactured by blown film or a cast film process (Butler & Morris, 2012). Usually it is made of co-extruded Low-Density PE (PE-LD) and Linear Low-Density PE (PE-LLD) (APC, 1997), but special applications might require minor amounts of such polymers as polypropylene (PP), ethyl vinyl acetate (EVA) or Ultra-Low-Density PE (ULDPE) to be used as layers. Figure 11 presents three examples of such compositions. For providing the required cling, a tackifier, for example polyisobuthylene, can be used on one or both surfaces. (Butler & Morris, 2012)

Figure 11. *Examples of structure and composition of stretch cling pallet wrap (Butler & Morris, 2012)*

Properties of PPW and flexible agricultural plastics were recently studied by Hiipakka and Lehtonen et al. The methods used in the studies vary. In 2012, Hiipakka audited the waste plastic streams and utilization of post-consumer plastic in Finland. She studied mechanical properties of flexible plastic wastes derived from agricultural waste stream and MSW wastes by pressing and shredding the waste films, compounding them with virgin material, producing samples with injection molding and analyzing them. The laboratory analysis of the samples included measurements of density, Melt Flow Rate (MFR), Shore hardness, tensile and flexural properties, Heat Deflection Temperature (HDT) and impact resistance (Hiipakka, 2011). In 2015, Ekokem Oy had a trial in washing and processing of agricultural films and flexible packaging from peat production. Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD) and concentration of P, NH_4, N, Na, Cl and suspended solids were measured from the cleaning water together with conductivity. Density, MFR and mechanical and thermal properties of the recyclate were measured also in this study. Despite initial heavy contamination with solids, washed and extruded recyclate could be processed into commercial-like films by both cast and blown film extrusion. The tensile properties of the recyclate were comparable to those of reference material. The presence of polyisobutylene from an adhesive (glue) on agricultural films made the material to feel moist and was expected to affect MFR. Also anticipated presence of high-density PE (PE-HD) was expected to affect MFR. (Lehtonen, et al., 2015)

Regulations is essential source of information both regarding the raw materials for recycling process or requirements, which produced pellets have to satisfy. Additionally, existing recycling targets might provide the incentive for the recycling.

The already mentioned PPWD[22] limits the total concentration of lead (Pb), cadmium (Cd), mercury (Hg) and hexavalent chromium (Cr(VI)) in packaging to 100 ppm (EPC, 2015). In line with it, §5 of Governmental Decree 518/2014 limits an aggregated amount of these metals to maximum 100 mg per kilogram of packaging weight in any brought to the market packaging or its easily separable parts (FINLEX, 2014).

[22] Directives 94/62/EC

According to the PPWD and amending it Directive (EU) 2018/852, a Member State should ensure that by the end of 2025, minimum 65 w% of all packaging waste will be recycled and minimum 50 w% of plastic contained in packaging waste is recycled. By the end of 2030 these numbers should increase to 70 % and 55 % correspondingly. For the calculations of the targets the amount of packaging waste should be taken as packaging placed on market at the same year and weight of packaging recycled should be calculated as weight of sorted packaging waste entering the recycling operation (EPC, 2015; EPC, 2018).

5.1.1. Recovery process and materials

Choice of input waste, processing included in the recovery process and output candidate for the assessment were dictated by materials and equipment available for the author and time constrains.

The candidates chosen for the assessment are presented with in the table 10 below. In the table the coding for candidates used in the text are explained - in each code C letter stands for Candidate.

Table 10. *Description of recovery process and materials, assessed within the first case study*

Code	Description of the candidate	Input material for the recovery process	Recovery process
C1	PE-pellets produced from transparent industrial/commercial packaging waste	Collected in Finland post-consumer industrial/commercial packaging, classified as PE-LD and excluding labels and tapes	visual assessment, removing of accidental contamination, pressing and shredding, compounding
C2	PE-pellets produced from industrial/commercial packaging waste, containing labels and tapes	Collected in Finland post-consumer industrial/commercial packaging, classified as PE-LD and including labels and tapes	visual assessment, washing, drying, pressing and shredding, compounding
C3	PE-pellets, produced from packaging waste	Collected outside of Finland plastic packaging	Limited information available; recycling stage included filtering

The major difference between analyzed materials was in availability of information – the samples of materials C1 and C2 were handled by the author from the collection of input waste to the analysis of the material properties, while the sample of C3 pellets was available from unspecified manufacturer. No information on input material for C3 was available, except that it was collected and recovered outside of Finland. An extra melt-filtration stage was used during the recycling process of C3 intended for removing of odor.

Raw material for C1 and C2 candidates was provided by one of collection/pre-treatment facilities in Finland. In this facility, commercial/industrial post-consumer flexible packaging are collected in 300 kg bales from the waste producers. The incoming waste is visually inspected, and the films are identified as PE-LD, using assistance of hand-held NIR-equipment, if necessary. During the same inspection, the films are graded. A grade consists of transparent PE film with no labels or tapes and no apparent contamination present. B grade can have some labels and tapes attached. Grade A and B then stored separately and later re-baled into 500 kg bales for the delivery to the customers. Bales are stored outside, but under the roof. The facility has estimated that usual mix of industrial packaging delivered to them consisted of 70 % grade A and 30 % grade B.

For manufacturing of C1 sample, author collected samples of A grade and for C2 sample – of B grade of input material at the waste collection/pre-treatment facility. Collection of samples happened by opening the random 300 kg bales and collecting 3-5 kg per material. As direct focus of present work was on demonstration of waste status termination, rather than characterization of the specific material, samples were considered representative based on visual evaluation, but no elaborated effort was payed to ensure representativeness of the samples.

Samples of input waste were visually inspected in the laboratory. The sample used for preparation of C1 pellets consisted of 85 % of stretch wrap and 15% of flat film. The sample used for preparation of C2 pellets included 15 % of stretch wrap, 82% of flat film and bags and 3% of foamed packaging, bubble wrap and hard packaging. The input waste samples are presented on figure 12.

Figure 12. *C1 (a) and C2 (b) input material samples*

Sample used for manufacturing of C2 was washed, as it was visually dirty and had an unpleasant odor. Washing was performed in a bucket in lukewarm water. The films were soaked and sheared with hands for friction to remove all the content affected by water. As a result, all the fiber containing content, such as labels, was removed to the extent that only whitish base would remain (see figure below). Also, non-water-washable labels and tapes remained. The films were then drained of water excess and dried by spreading on the floor and rotating for 10 days. The washing water was sieved and analyzed for visual contamination.

Figure 13. *Remaining of adhesive on the washed sample of input waste for C2*

The sample used for preparation of C1 was not washed. It contained one plastic label and some plastic tape (0.3 % of sample), see figure 14. That contamination was removed prior to processing from the dry films.

The sample used for preparation of C2 contained one PET container (1% of sample weight) and contaminants presented on figure 15 below, namely paper (1 % of sample), plastic tape (0.3 % of sample); metal (0.1 %). All contaminants were removed prior to further processing.

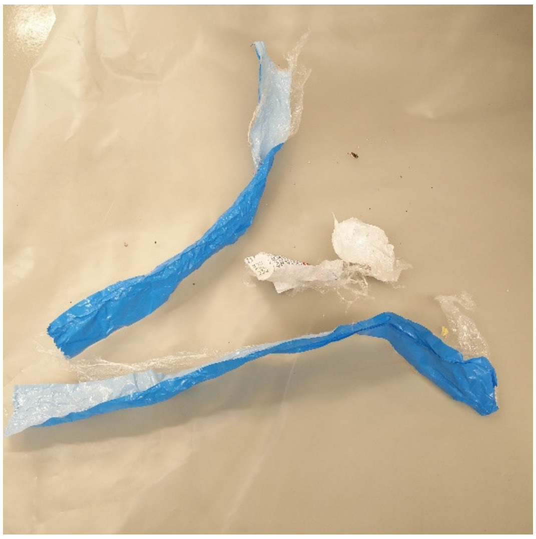

Figure 14. *Contamination removed from sample, used for C1 pellets manufacturing*

Figure 15. *Contamination removed from sample, used for C2 pellets manufacturing*

Waste film for C1 and washed and dried film for C2 were both first pre-ironed into thin sheets and then pressed in a press into thicker, 350-450 g sheets with 105-110 ºC and 15 bars. The thin sheets for sample C1 were prepared by sandwiching stretch wrap between the flat film. The stretch wrap was sometimes in nodes, but they were opened and film was folded whenever possible. The thin sheets for C2 sample were prepared by sandwiching all films in between flat films. Despite a long drying period, some moisture was still trapped between the layers of stretch wrap of sample C2. Moist-containing stretch wrap pieces were manually ventilated and placed in the middle of the sandwich (with edges not sealed), so that moisture could escape on heating.

The pressed sheets were then cut by the saw in around 5*3 cm pieces for feeding into shredder, shredded into 5-8 mm pieces and compounded. Compounding of C1 and C2 was performed with twin screw extruder with L/D ratio of 38. The materials were extruded at 180-200 ºC, strands were cooled with water and cut to pellets. Melt was degassed during the process. The pictures form steps of the processing are presented in figure 16.

Figure 16.*Top: Preparation of C1 pellets: pressed sheets (left); cut pieces for shredding (middle); compounded pellets (right). Bottom - same sequence for manufacturing of C2 pellets*

Compounded pellets were blended with virgin polyethylene and used for production of a film with Collin blown film lab-scale line. The temperature profile used for extrusion was 180 – 190 – 200 °C (cylinder/adapter/die), die diameter 60 mm and line speed 4 m/min. Fraction of recycled to virgin pellets was 25 w%. Target thickness of the film produced was 40 micrometres. Virgin pellets used in the mix were also used as reference material for the rest of the testing. Properties of the reference material are presented along the properties of the EoW candidates in the chapter 6.

5.1.2. Material status assessment

For assessment of pre-requisites for termination of waste status, the author used criteria presented in the table 11. The choice of the criteria was not straightforward, as no methodology for such an assessment is available for Finland. The final choice of assessment criteria was based on legislation, texts by Villanueva et al., examples of Quality Protocols from England, technical guidelines for recyclers by Ökopol Institute and other sources of information, presented in the literature review. Choice of laboratory methods was based on standards reviewed and expertise of Borealis experts available.

One of the legal pre-requisites for EoW candidates is meeting product legislation. Analyzing of all regulations, related to all possible applications of produced pellets, is virtually impossible, therefore the application was set to be a non-food contact film. That choice was based on the knowledge, that the original application of the waste was an industrial packaging film, therefore the original material had fulfilled the technical and legal requirements set for the film grade PE-LD and potentially could be used for that purpose.

Table 11. *Criteria used in material status assessment and sources of information inspected for assessment, case study packaging*

Criterion	Knowledge required	Sources of information
Compliance with registration requirement under REACH	Identity of the polymer, which constitutes > 80 % of the recyclate.	Instructions, according to which the waste was collected Resin Identification Code NIR-identification Visual assessment SFS- EN 15347 ECHA web site Laboratory analysis
Compliance with information requirement under REACH and CLP	Presence of any components that trigger classification as hazardous according to CLP regulation.	Positive knowledge that the hazardous substances are not present (see main text for details) SFS- EN 15347 SFS-EN 15343 ECHA web site PPWD Governmental Decree 518/2014
Compliance with communication requirement under REACH	Presence of any components that trigger classification as hazardous according to CLP regulation. Knowledge of exposure scenarios of the registered substances	Similar to the previous one
Compliance with EU and national product regulations (packaging, excluding food contact)	Content of lead (Pb), cadmium (Cd), mercury (Hg) and hexavalent chromium (Cr(VI))	PPWD Governmental Decree 518/2014 SFS- EN 15347 Laboratory analysis
Suitability of produced pellets for plastic converters	Properties, suggested in a standard for characterization of recycled PE	SFS-EN 15344 Laboratory analysis
Suitability of produced pellets for manufacturing of film	Properties, measured for a typical film grade polymer: Density, MFR, Melting temperature, Dart drop, tensile properties, color	Film-grade PE-LD generic data sheet Laboratory analysis
Quality assurance of the recyclate Traceability of substances through the recycling chain Statement of recycled content (optional)	Properties, suggested in a standard for traceability and assessment of conformity	SFS- EN 15347 SFS-EN 15343 Quality system of recycler Communication with waste film collecting facility Laboratory analysis

5.1.3. Laboratory analysis

For obtaining FT-IR spectrum, Bruker Tensor 27 Spectrometer was used fitted with ATR crystal. The wavenumber range of 500 – 5000 cm^{-1} was used for scanning.

For obtaining DSC curves, representative 5-10 mg samples were analyzed with Mettler Toledo DSC 2 thermal analyzer equipped with STARe system. The samples were subjected to two heatings at 10 ºC/min in inert atmosphere from 30 to 300 ºC and cooling of similar rate. The analysis was performed according to ISO 11357-3 standard.

For X-Ray Fluorescence Spectroscopy (XRF), the materials were pressed in sheets and analyzed with S4 Pioneer XRF Spectrometer.

Determination of melt mass-flow rate (MFR) of materials was performed with Göttfert MI-4 Melt Indexer according to ISO 1133-1 standard, method A. Temperature and weight used for the test were 190 ºC and 2.16 kg.

Apparent density was measured according to ASTM D1895 standard, method B. Density of the materials was measured according to ISO 1183 standard with Mettler Toledo AX 105 Delta Range balance. Density of the isododecane at determination instance was 745.85 kg/m^3.

Determination of ash content was made according to ISO 3451-1 by pre-burning the bulk of a sample with Bunsen burner and complete incineration of the residue in muffle furnace during 30 min at 750 ºC.

Determination of moisture content was performed according to ISO 15512 (Karl Fisher method) with Metrohm 831 KF Coulometer.

Colour determination of pellets and films was performed with Datacolor 650 Spectrophotometer following ISO 11664-4 or ISO 11664-2 standard.

Pellet shape and size distribution was determined with modular OSC PA 66 pellet analyser combined of PS-25 C and PSSD modules.

Determination of impact resistance of the blown film was made according to ISO 7765-1 standard with Davenport dart drop testing equipment. Drop height was 66 cm and diameter of the dart used 38 mm.

Determination of the tensile properties of the blown film was performed with Instron 4502 equipment according to ISO 527-3. The 100 N load cell and crosshead speed of 500 mm/min was used. The test was performed at 23 ºC and 50 % RH and samples were preconditioned for the time, required by the standard. Five film samples were used for each test. The thickness of each sample was calculated by averaging the results of three manual thickness measurement made with micrometre.

5.2. Plastic pipes

Being a class of construction products, pipes waste can be found in construction and demolition waste (C&D). In Finland C&D waste is waste produced during original construction, renovation or demolition of buildings and construction of road- and water infrastructure (FINLEX, 2012). According to Finnish waste statistics, around 1.8 M of other than landmasses C&D wastes was generated in Finland in 2016 (Suomen virallinen tilasto (SVT), 2016).

In literature describing Finnish wastes, C&D waste is divided into new construction waste, demolition waste and renovation waste (Salmenperä, et al., 2015; Ronkanen, 2016). Examples of wastes generated during new construction activities are packaging and poorly protected and spoiled materials (Korpivaara, et al., 2013). Materials found in demolition waste are usually old and used for 30 years or longer (Ronkanen, 2018). Renovation waste is described by some authors as a combination of new construction and demolition wastes (Ronkanen, 2018).

Construction waste can be divided in waste produced in house construction, waste produced in earth and water construction and waste produced in specialized construction activities

(Salmenperä, et al., 2016). At collection/pre-treatment facilities such theoretical division might not be followed, and C&D waste will be collected from all types of real estate- and infrastructure construction and demolition (Ronkanen, 2018). In 2011-13, 15-18 Mt of construction waste was produced in Finland (Laaksonen, et al., 2017; Korpivaara, et al., 2013). Around 1.8% of construction waste is hazardous (Korpivaara, et al., 2013) From all construction waste around 10% is originated from house construction and the rest - from earth construction waste (mainly mineral waste) (Laaksonen, et al., 2017).

Information on composition is mostly available regarding house construction waste. It is reported that almost three quarters of that waste are from renovation activities and new construction (see figure 17).

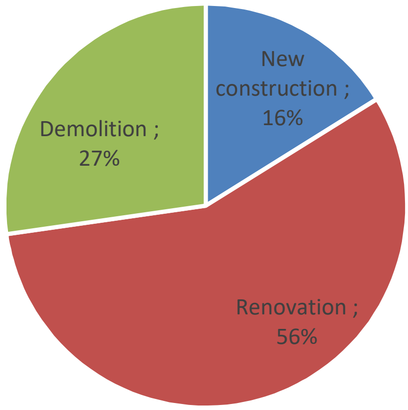

Figure 17. *House construction waste by origin (Salmenperä, et al., 2015; Korpivaara, et al., 2013)*

It is also reported, that house construction waste contains around 40% waste wood, around 31% mineral waste and around 14% metal waste. Additionally to those, house construction waste contains some amounts of plastic waste such as insulation and packaging, paint waste, glass and municipal waste-like waste (Salmenperä, et al., 2015). In 2014 in Finland 58% of house construction waste were recovered as material, 32% as energy and 10% were sent to landfill (Laaksonen, et al., 2017).

In a study addressing development of sorting of C&D waste, composition of mixed C&D from two samples was evaluated. The first sample contained new building construction and renovation waste, while second – only renovation wastes. Content of plastic in the first sample was found to be 16% and in the second – 14%. Plastic fraction analyzed contained 43% hard plastics (not PVC, PS or EPS) and 14% flexibles. Plastic fraction from the second sample contained 62% flexibles and 17% hard plastics (not PVC, PS or EPS) (Ronkanen, 2016). Among other fractions, the first sample contained 14 % of wood and 4% of concrete and the second sample – 21% of wood and 0% concrete, what differs significantly with values reported by Salmenperä at al (Salmenperä, et al., 2015). The explanation for the difference could be in a fact that composition of the mixed C&D waste delivered to the handling facilities does not represent all Finnish house C&D waste. Gate fees provide the incentive for the waste producer to separate mineral and wood fractions (Ronkanen, 2018), what results in lower content of these fractions is mixed C&D waste.

In 2012, separate collection of plastic C&D waste was not too common, and it was mostly collected as part of energy waste (Merta, et al., 2012). Nowadays, for example in instructions of Destaclean Oy, one of the companies collecting and managing C&D waste, plastics (except PVC) can be found in three collectable fractions (Destaclean, 2018):

- recoverable mixed construction waste, consisting of wood, plastics, paper and other packaging material

- source-separated packaging, containing clear plastics (HDPE and LDPE) and cardboard
- source-separated energy waste, containing waste suitable for energy recovery, such as wood, plastic, insulation material, cardboard and paper

In 1999, Finnish Plastics Industries Federation started a trial voluntary separate collection of plastic pipes. The collection points were set in conjunction to wholesale points to where the installation company could return the residues of the pipes as the new pipes would be purchased. Additionally, water treatment companies were returning the pipes directly to recycler. The produced re-granulate would be sold back to the pipe producers. After original spike of 150 t/a, the collection amounts started dropping. Some of the reasons were collection points of pipe waste organized directly by recyclers and returning of pipes together with other fractions containing plastics. Additionally, presence of other-than-pipes contamination in collection containers was reported. As the result of problems arising from collection, the trial was concluded in 2011 (Merta, et al., 2012).

Industrial reports account that in Finland the first plastic pipes were taken in use in 1950s and nowadays around 80% of Finnish water and sewage system is made of plastic. Use of plastic as a pipe material is more common in Finland that on average in Europe. Most common production method is extrusion (Muoviteollisuus ry, 2009). The first PE-HD pipes came to the Finnish market in 1960s (Kneck, 2018). When compared to pipes made of concrete and metal, PE plastic pipes can be characterized by light weight and resulting ease in transportation and installation. Possibility to install longer pieces of pipes, supplemented by materials' flexibility, result in decreased need for jointing, which, in turn, result in less faults. Inertness, chemical resistance, toughness even at lower temperatures and fatigue resistance are other sought-after properties (Muoviteollisuus ry, 2009; Plastic Pipe Institute, 2008). On the other hand, sensitivity of PE pipe properties to temperature and duration of loading and variation of mechanical response of pipe with nature of PE, additives and other added components chosen (Plastic Pipe Institute, 2008), requires a certain degree of expertise in material science for efficient and safe use.

The author did not find any documentation describing the quality of Finnish PE-HD pipe waste. In the report by Villanueva and Eder it is mentioned that thermoplastics used in construction can be characterized by long life-span, need of high impact resistance and UV-stability and relatively high content of fillers (Villanueva & Eder, 2014). The properties of the specifically PE-HD pipe wastes can be concluded from the specifications of the pipes. Unlike other construction products, which are controlled by regulation (EU) No 305/2011[23] and for which CE-marking and Declaration of Performance should be obtained, for time being quality of plastic pipes is most often proclaimed with NPM mark (Muoviteollisuus ry, 2018). NPM-mark is a quality mark that verifies that the manufacturer of the products complies with certification scheme established by an independent certification body (NPM, 2018). Additionally to NPM-mark, a standard according to which the pipe was produced can be found on the side of the pipe. For example, according to the standard EN 12201 *Plastic piping system for water supply, and for drainage and sewage under pressure – Polyethylene (PE)*, the minimum marking required on the side of the pipe includes, among other things, the intended use (drinking water, sewage), raw material with strength designation and manufacturer (EN 12201-2:2011, 2013). On non-pressure pipe, the marking also includes reference to standard, but the material is stated without strength designation (SFS-EN 13476-3:2018, 2018).

No study on properties of recycled PE-HD made from Finnish pipes was found. In 2016, Mylläri et al. have studied effect of multiple extrusion and effects of detergent on properties of local recycled PE-HD originated from separately-collected hard packaging stream. The research group simulated the effect of contamination of recycled material by adding 3 w% of liquid detergent to PE-HD prior to pre-extrusion drying step. Rheological and mechanical properties change in crys-

[23] Regulation (EU) No 305/2011 lays down harmonised conditions for the marketing of construction products

tallinity, OIT, Volatile Organic Compounds (VOC) levels and presence of LMW groups were analyzed. The study has found that addition of detergent to the recycled material affected rheological properties by acting as a lubricant. Continuous extrusion resulted in increase of 10-20% of tensile modules; other tensile properties were affected less. Addition of detergent, in turn, decreased the modulus back to the level of virgin material. Little effect on melting point was observed, while crystallinity of the aged and contaminated samples decreased. Finally, addition of detergent associated with decreased OIT, higher total VOC emissions and accumulation of a product of dimerization of ethylene oxide (Mylläri, et al., 2016).

There are no Finnish national standards on quality assurance of plastic recyclates, but the example can be taken from SFS 5884:2018 *"Factory Production Control of crushed concrete for earth construction*". This voluntary standard explains that quality control system allows the producer of the crushed concrete to prove that its material complies with technical and environmental requirements set by application in earth construction. The burden of quality control falls on the producer of the crushed material. The standard states that the quality control system should cover all the stages from the reception of the waste or demolition stage until the delivery to the user. It is the responsibility of the crushed concrete producer to ensure that the material complies with the requirements and to obtain CE marking for it or to produce a product specification. Additionally, producer is required to produce instructions for design- and operations involving its crushed concrete. The compliance of the crushed concrete is to be demonstrated with CE-marking, Declaration of Performance and possibly measurements of granulation. CE marking is not required, if the product is produced and used at the same location under the same ownership. The standard defines the requirements for the education, responsibilities and authority of the personnel that controls, performs and audits any activities affecting the quality. It also defines the requirements for documentation of reception and storage of concrete waste, requirements for production, sampling and quality control. Two types of sampling are distinguished – for quality control of compliance with technical requirements and for control of compliance with environmental regulations. Additionally, the standard contains instructions on transportation and packaging of crushed concrete and specifies the spectra of parameters to be tested to prove both technical and environmental compliance. Classification guide of crushed concrete is also included in the standard (SFS 5884:2018, 2018).

5.2.1. Recovery process and materials

Materials used and processing performed within the second case study are presented in the table 12.

Table 12. *Description of recovery process and materials, assessed within the second case study*

Code	Description of the candidate	Input material for the recovery process	Recovery process
C4	PE-pellets produced from plastic pipes	Collected in Finland pipes separated from post-consumer C&D waste and visually identified as PE	Shredding, washing, additional shredding and compounding

Input plastic waste was plastic pipes from C&D waste. Currently, waste plastic pipes stream does not exist on its own in Finland and separate collection of pipes is sporadic. The pipes for the case study originated from a stream of mixed construction and demolition waste collected at one of the collection/pre-treatment facilities. Stream of mixed C&D waste included wastes from house and infrastructure construction and demolition. The pipes were separated by a small excavator equipped with a grapple and later visually inspected. Only non-broken, tidy looking, black pipes with a marking on the side were taken for the case study. Marking on the side, stating the material of the pipe to be PE, was used for identification of material.

Separated pipes were then shredded with Untha LR630 shredder with screen size 10 mm and washed with a regular washing machine without chemicals. This part of the processing has taken place at collection/pre-treatment facility. For manufacturing of sample of C4 material, a 3 kg sample of material shredded and washed by the collection/pre-treatment facility was used. It was recycled in the laboratory. The recycling included shredding of the sample with Rapid 150 shredder into 3-5 mm pieces and compounding. Compounding of C4 was performed with twin screw extruded with L/D ratio of 38. The materials were extruded at 180-200 ºC at 150 rpm, the strands were cooled with water and cut to pellets. Melt was degassed during the process and no additives or property-modifiers were added.

5.2.2. Material status assessment

In a similarly to the first case study manner, the criteria for waste status assessment of material C4 are provided in the table 13.

Table 13. *Criteria used in material status assessment and sources of information inspected for assessment, case study pipes*

Criterion	Knowledge required	Sources of information
Compliance with registration requirement under REACH	Identity of the polymer mix, with constitutes > 80 % of the recyclate.	Instructions, according to which the waste was collected Visual assessment Marking on the side of the pipe SFS- EN 15347 Laboratory analysis
Compliance with information requirement under REACH and CLP	Presence of any components that trigger classification as hazardous according to CLP regulation.	Existence of positive knowledge that the hazardous substances are not present: documentation from the collecting facility, stating that no mixing with hazardous materials has taken place. Marking on the side of the pipe SFS-EN 15343
Compliance with communication requirement under REACH	Presence of any components that trigger classification as hazardous according to CLP regulation. Knowledge of exposure scenarios of the registered substances.	Scientific literature containing chemical analysis of the waste stream and recyclate OR representative chemical analysis. Efficient communication with suppliers of the registered substances or waste producers Marking on the side of the pipe
Suitability of produced pellets for plastic converters	Properties, suggested in a standard for characterization of recycled PE	SFS-EN 15344 Laboratory analysis
Suitability of produced pellets for manufacturing of pipes	Properties, required by the non-pressure pipe standard	Laboratory analysis SFS-EN 13476-3:2018 Marking on the side of the pipe
Quality assurance of the recyclate Traceability of substances through the recycling chain Statement of recycled content (optional)	Properties, suggested in a standard for traceability and assessment of conformity	SFS-EN 15343 SFS- EN 15347 Communication with waste film collecting facility Laboratory analysis

5.2.3. Laboratory analysis

For obtaining FT-IR spectrum, Bruker Tensor 27 Spectrometer was used fitted with ATR crystal. The wavenumber range of 500 – 5000 cm^{-1} was used for scanning.

For obtaining DSC curve, a representative 5-10 mg sample was analyzed with Mettler Toledo DSC 2 thermal analyzer equipped with STARe system. The sample was subjected to two heatings at 10 ºC/min from 30 to 300 ºC in inert atmosphere and cooling of similar rate. The analysis was performed according to ISO 11357-3 standard. The determination of oxidation induction time (OIT) was performed with the same thermal analyzer according to standard ISO 11357-6. For this test an approximately 1 mm thick piece of extruded homogenous string of 5 mm in diameter was placed into Al crucible and heated with 20 Cº /min from 25 Cº to 200 Cº in inert atmosphere. After 5 min the ambient gas was changed to oxygen, which was fed at 50 ml/min.

For X-Ray Fluorescence Spectroscopy (XRF), the material was pressed in sheets and analyzed with S4 Pioneer XRF Spectrometer.

Determination of melt mass-flow rate (MFR) of material was performed with Göttfert MI-4 Melt Indexer according to ISO 1133-1 standard, method A. Measuring temperature and weight used for the test were 190 ºC and 5 kg.

Apparent density was measured according to ASTM D1895 standard, method B. Density of the material was measured according to ISO 1183 standard with Mettler Toledo AX 105 Delta Range balance. Density of the isododecane at determination instance was 745.85 kg/m^3.

Determination of ash content was made according to ISO 3451-1 by pre-burning the bulk of the sample with Bunsen burner and complete incineration of the residue in muffle furnace during 30 min at 750 ºC.

Determination of moisture content was performed according to ISO 15512 (Karl Fisher method) with Metrohm 831 KF Coulometer.

The determination of carbon black content was performed according to standard ASTM D 1603. For this test around a representative 1 g sample was kept for 20 min at 550 Cº in inert atmosphere.

Colour determination of pellets was performed based on visual inspection.

Pellet shape and size distribution was determined with modular OSC PA 66 pellet analyser combined of PS-25 C and PSSD modules.

Determination of the tensile properties was performed with Zwick Roell Z010 equipment according to ISO 527-2. The sample of type 1A, 5 kN load cell and crosshead speed of 50 mm/min was used. The test was performed at 23 ºC and 50 % RH and samples were preconditioned for the time, required by the standard.

6. RESULTS AND DISCUSSION

6.1. Material status assessment of packaging-derived PE pellets

First, registration requirement under REACH was assessed. According to it, the recovered substance has to be re-registered, unless it complies with the rules for exception (see the section 4.2.3 “Requirements under REACH and CLP” for details). The following information was collected for the assessment:

For the beginning, waste material was inspected and information was compiled, according to EN 15347 standard, see table 14. The method, according to which each parameter in the table had to be defined, was not specified in the standard, so the information provided is the interpretation of the characteristic by the author.

Table 14. *Information, compiled for post-consumer plastic packaging waste according to standard EN 15347*

Required characteristics	C1	C2	C3
Batch size	500 kg	500 kg	No information
Color	Transparent	Transparent	
Form of waste	Baled film	Baled film	
History of waste	Packaging	Packaging	
Main polymer present	PE-LD	PE-LD	
Other polymers present	Presumably none	Presumably none	
Packaging	Iron ropes	Iron ropes	
Additives, contaminants, moisture, volatiles (optional characteristic)	Possible rust from packaging ropes	Max. 5 % of tapes and labels, based on visual inspection Possible rust from packaging ropes	

The information in the table 14 is compiled based on the description of the waste provided by collection/pre-treatment facility. Visual inspection and manual sorting of the samples in the laboratory have shown that contamination of the input material for C1 included 0.3% extraneous polymers (plastic tape and label) and for C2 included 1.3% extraneous polymer (PET container – 1% and plastic tape -0.3% of sample weight respectively) and 1.1% of other materials (paper - 1% and metal - 0.1% of sample weight). All the contamination was removed prior to further processing.

The information provided by collection/pre-treatment facility and obtained in the course of recycling process was compiled according to the standard EN 15343 and presented in the table 15.

Table 15. *Information, compiled according to standard EN 15343 for evaluation of traceability and quality assurance during reprocessing of C1, C2 and C3 materials*

	C1	C2	C3
Origin			
Material type/form	PPW	PPW	PPW
Product type	Large films	Large films	No information
Type of waste	Post-consumer waste	Post-consumer waste	Post-consumer waste

Where is it came from	Industry/commerce	Industry/commerce	No information
History of waste	Packaging	Packaging	No information
Date	8.6.2018	8.6.2018	No information
Logistics			
Collection	Source-separated. 300 kg bales are delivered to collection/pre-treatment facility in Finland.		Collected outside of Finland
Sorting	Bales are opened and visually inspected. Material of the packaging waste is confirmed to be PE-LD. Handheld NIR analyzer is used, if necessary, for confirmation of plastic type. Level of contamination is visually identified, grade assigned: A grade for visually not contaminated and B – when labels and taping are present. Films are de-baled into new 500 kg bales and stored until delivery to a customer. Iron ropes used for keeping the bales together cause sometimes rusty marks on the side of the bales.		No information
Batch size, identification and marking	500 kg of PE-LD waste film, A grade	500 kg of PE-LD waste film, B grade	No information
Pre-treatment	None	None	No-information
Storage	Outside, under roof, time varies from a few weeks to a few months		No-information
Analysis before processing	Waste characterization according to EN 15347 Visual examination NIR-identification		
Process parameters	Sample was taken from both input materials. Sample for C2 was washed. Visible contaminants were removed from both samples. Both samples were pressed into sheets, cut into pieces and shredded. Shredded material was compounded with twin screw extruded with L/D ratio of 38. The materials were extruded at 180-200 ºC, cooled with water and pelletized. Melt was degassed during the process. No substances were added during the process.		Recovered outside of Finland. An extra melt-filtration stage was used during the recycling process intended for removing of odor.
Analysis after processing	According to EN 15344 and generic application data sheet		
Intended application	Industrial film	Industrial film	No information

Main polymer of the input material for C1 was identified as PE with visual inspection and handheld NIR. ISO 18263, defining methods for determining properties of PE/PP recyclate derived from consumer packaging, prescribes to determine composition of the material (PE/PP ratio) in accordance with traceable documents from the supplier. Therefore, based on information provided by supplier of the waste, material of the waste input can be identified as 100% PE.

In order to confirm that information, the FT-IR spectrum and DSC scans were obtained in the laboratory. According to FT-IR analysis, the main polymer present could be identified as PE. Figure 19 presented below shows DSC curves of EoW candidates and a reference PE-LD material. DSC endotherm of a reference PE-LD material exhibits a single melting at 112 ºC. On contrast, endotherms of all three EoW candidates have multiple melting peaks, what probably implies the presence of two polymers. Using the DSC curves of PE-LD/LLD blends available in the literature (Wu, et al., 1991), the material was identified as mixture of LD-PE and LLD-PE, what is in line with information found in the literature on composition of stretch wrap (APC, 1997; Butler & Morris, 2012).

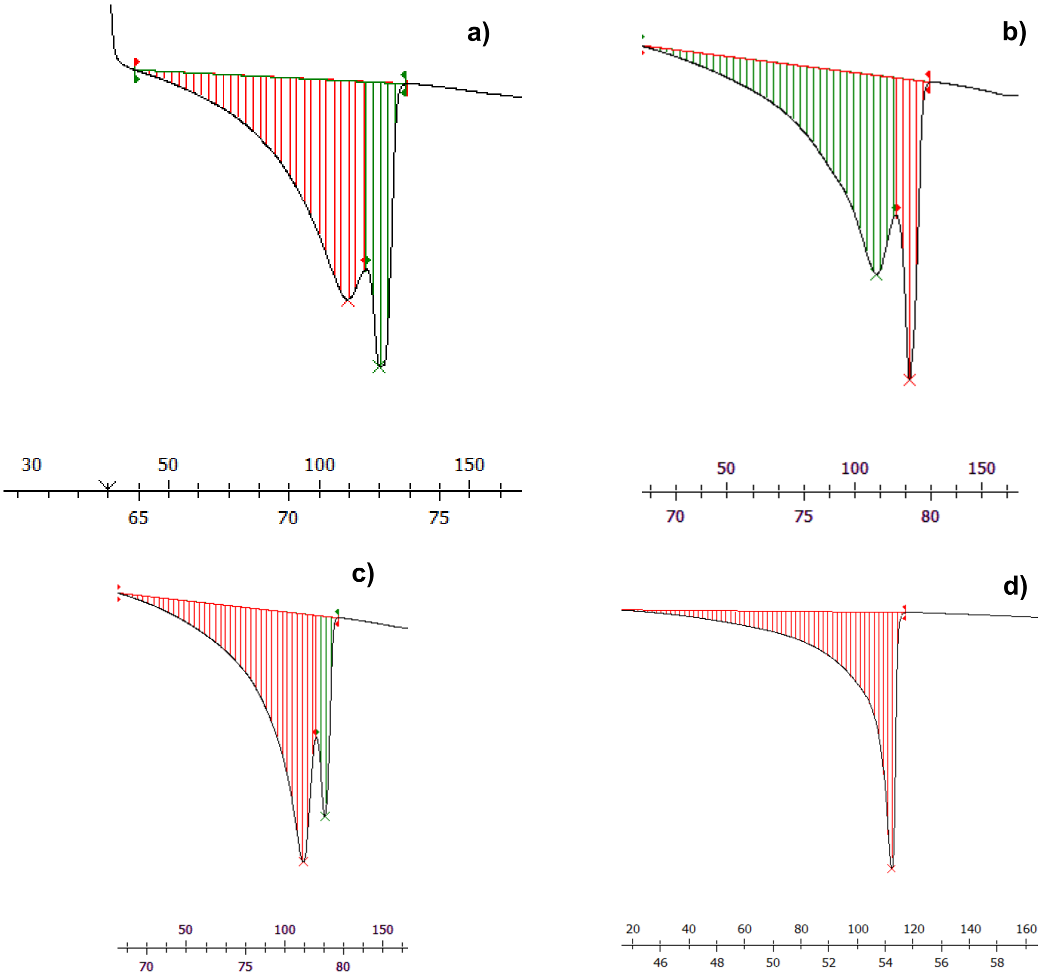

Figure 18. *DSC curves for EoW candidates and reference material showing second heating cycle: a) C1; b) C2; c) C3; d) reference PE-LD material. Upper numbers on the ruler denote temperature.*

In order to comply with registration requirement of the REACH, more than 80 % of the monomers of the recovered polymer should be the same as already registered monomers, as polymers themselves do not have to be registered. ECHA website provides the information on identity and manufacturers of registered substances serving as monomers for production of polyethylenes of varying densities (ethylene, 1-butane, 1-hexane, 1-octene). For example, ethylene has EC/List number 200-815-3 and CAS number 74-85-1.

The fraction of non-organic content of the recovered materials was measured to be below 1% (see table 16). That non-organic fraction can be considered as impurity and does not have to be registered.

The second and third criterion in the assessment were compliance with information and communication requirements under REACH and CLP. According to them, presence of any component in the recovered substance that would trigger classification as hazardous according to CLP would require appropriate classification, labeling, packaging and communication to the user.

Regarding the polyethylene, ECHA web site states "*According to majority of notifications provided by companies to ECHA in CLP notifications, no hazard has been classified. At least one company has indicated that the substance classification is affected by impurities or additives*" (ECHA, 2018). PE-LLD/LD usually does not include any added components that contain hazardous substances, with exceptions to some colorants (Hansen, et al., 2013). Input waste to C1 was only transparent packaging.

In addition, as input to the recovery process for C1 was only packaging, at least the presence of such elements as Pb, Hg, Cd or Cr (VI) in the material is already restricted due to legislation (EPC, 2015; FINLEX, 2014).

The information, compiled according to standard EN 15343, provided the author with confirmation that waste material used as input for C1 has not being in contact with any hazardous substances during or after collection or during the processing.

The information provided in the previous three paragraphs, suggests that raw material used for manufacturing of plastic packaging does not trigger CLP classification as hazardous, neither the processing of waste results in change of hazardous profile.

There are some other potential sources of hazardous substances, namely possible property-modifiers, tie and extra polymers layers, coating and printing ink added to polyethylene during manufacturing of packaging; labels and packaging tape added during the packaging process and contact with hazardous substance during the use of packaging.

Absence of hazardous substances, during manufacturing of packaging can be suggested, based on the technical literature (Hansen, et al., 2013). The absence of contact with hazardous substances during the use phase can be suggested by the statement produced by the collection/pre-treatment facility upon inspection of arriving waste and documented according to standard EN 15343.

Based on the analysis of the packaging, it did not contain other than PE-LD and PE-LLD polymers, neither was coated. Waste used for manufacturing of C1 was free of labels, adhesives, packaging tape and ink.

Given all the considerations presented in the previous three paragraphs, the author concludes that there is sufficient evidence, that C1 material does not contain any substance that might trigger its classification as hazardous.

Waste used for manufacturing of C2 after washing was free of paper labels, but had some leftovers of the adhesives, plastic labels with ink and some tape attached. As any components of packaging, including attached to it sticky labels and inks, are subject to PPWD (EPC, 1994), also other than polyethylene materials present in or on packaging are expected to be subject to limitation in amount of Pb, Hg, Cd or Cr (VI). Nevertheless, there is no sufficient evidence, that C2 material does not contain any other than Pb, Hg, Cd or Cr (VI) substances potentially originating from an adhesive, ink, a label or a tape. Therefore, the material C2 can contain some substance that might trigger classification as hazardous according to CLP.

In order to confirm that the EoW candidates do not contain substances that are not allowed in packaging, the XRF analysis was preformed (see table **16).**

Table 16. *Variables, tested to verify compliance of C1 and C3 material with REACH and CLP requirements*

	C1	C2	C3
Ash content	Ash residue 0.49 %, 4 856 ppm	Ash residue 0.89 %, 8 882 ppm	Ash residue 0.67 %; 6 735 ppm
Presence of metals and inorganic components (XRF)	Ca, Zn, Si, Fe, P, Al	Cl, Ca, Si, Fe, Ti, Na, Al, S, Zn, K, Mg, P	Ca, Cl, Si, Al, Na, Mg, Fe, Zn, K, Ti, S

Compliance with EU and national legislation of packaging and its parts supplemented with results of XRF analysis provide the sufficient basis for suggesting that the recycled materials C1, C2 and C3 can be used in packaging application.

As information about C3 regarding the history and nature of the input waste, no assessment could be done regarding compliance with REACH and CLP regulations.

For the technical assessment, the suitability of the manufactured pellets for manufacturing of plastic items (in general, according to standard 15344) and of film in particular (according to generic film grade data sheet) was assessed. The tables below present the information collected.

Table 17. *Information, collected for C1, C2 and C3 materials according to standard EN 15344*

Property	C1	C2	C3	Reference material (TDS values)
Characteristics, identified by EN 15344:2007 standard as mandatory				
Bulk density	500 kg/m^3	479 kg/m^3	537 kg/m^3	Not commonly specified
Color	Slightly darker than reference	Darker and redder than C1 and C3	Slightly darker than reference	Natural white
Particle size and shape	Cylindrical small pellets, 3mm length, 110 pellet/g	Cylindrical small pellets, 3mm length, 105 pellet/g	Round and flat pellets about 6 mm in diameter, 36 pellets/g	Not commonly specified
MFR (190/2.16)	1.75 g/10 min	0.54 g/10 min	0.56 g/10 min	0.75 g/10 min
Characteristics, identified by EN 15344:2007 standard as optional				
Ash content	Ash residue 0.49 %, 4 856 ppm	Ash residue 0.89 %, 8 882 ppm	Ash residue 0.67 %; 6 735 ppm	Not commonly specified
Density	924 kg/m^3	936 kg/m^3	931 kg/m^3	923 kg/m^3
Moisture content	50 ppm	290 ppm	250 ppm	Not commonly specified

Additionally, few properties specific for film application of the pellets and properties of the films produced from the pellets were measured and presented in the table 18 below. The share of recycled material used for the film production was 25%. Average thickness of C1 film was 37 µm, C3 – 41 µm and reference PE-LD material – 38 µm. Thickness of C2 could not be reliably measured due to instability of the bubble during the film extrusion. Produced C2 film also contained significant amounts of gels and impurities. The figures 19 and 20 present the tensile properties of the films tested. Tensile strength of films with added C1 and C3 materials are comparable to the tensile strength of film, made completely of virgin material, both tested in machine (MD) and traverse (TD) directions. Tensile strength of film with added C3 material is lower. Tensile strain of reference virgin material does not decrease with addition of recycled material. Variation in measured values is higher for all films, produced with addition of recycled material.

Table 18. *Information, collected for C1, C2 and C3 materials based on suggested application as packaging*

Property	Testing method	C1	C2	C3	Reference material
Tm (DSC)	ISO 11357-3	Tm_1 109 ºC and Tm_2 120 ºC	Tm_1 108 ºC and Tm_2 121 ºC	Tm_1 109 ºC and Tm_2 120 ºC	112 ºC
Dart drop	ISO 7765-1	122 g	67 g	105 g	101 g
Tensile strain at break, MD/TD	ISO 527-3	227/270%	169 / 129%	203 / 196%	159 / 125%
Tensile strength, MD/TD	ISO 527-3	19 / 14 MPa	12 / 9 MPa	17 / 13 MPa	16 / 13 MPa

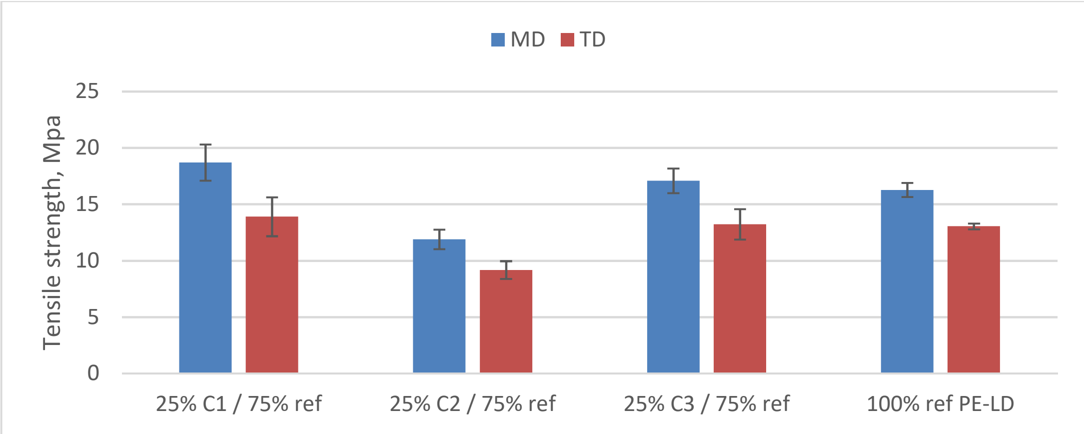

Figure 19. *Tensile strength of the films, produced with addition of C1, C2 and C3 materials and from reference material*

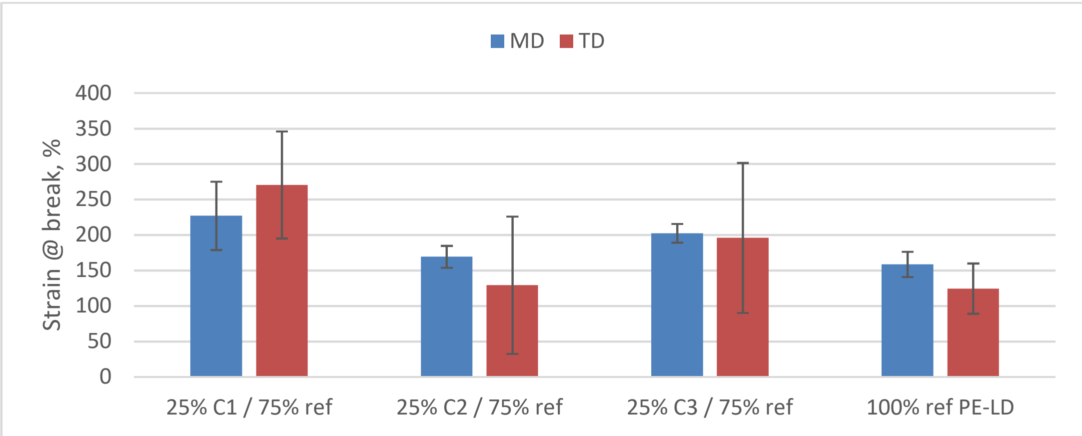

Figure 20. *Tensile strain at break of the films, produced with addition of C1, C2 and C3 materials and from reference material*

Based on the data provided in tables 17 and 18, the pellets size, bulk density and MFR of EoW candidates are in line with these parameters of raw materials used for film extrusion, therefore the recycled material can be used for that conversion process. Nevertheless, stability of the bubble during production of the 40 micrometers thick film was compromised with addition of 25 % of C2 material.

The effect of addition of 25 % of C1 and C3 materials to the reference virgin material could be concluded as neutral or positive and effect of addition of C2 as negative. Impact resistance improved with addition of C1 material, stayed the same with C3 material and decreased with addition of C2 material. Similar results are observable from tensile testing – addition of C1 and C3 material had no or little positive effect on tensile strength, while addition of C2 affects it negatively. Strain at break is rather low already for the reference material, what might be explained by non-optimal parameters during film blowing process, but addition of the recycled material at least did not make the material less flexible.

Comparing to the reference material, color of the films manufactured with addition of C2 pellets was darker and visible contamination was present in extruded film, what might affect the use of the material for the films, where clarity and transparency is required.

Combining all parts of the assessment, results in material C1 being the most likely candidate for waste status termination. Assessment is summarized in the table 19.

Table 19. *Summary of the waste status assessment for C1, C2 and C3 materials*

Material assessed	Compliance with regulations	Technical compliance
PE-pellets produced in Finland from transparent industrial/commercial packaging waste (C1)	Can be exempt from registration requirement, according to REACH With high probability does not contain any substance that might trigger its classification as hazardous Complies with national product regulations for packaging material	Can be processed with conventional extrusion equipment Can be used for production of film, at least in ratio of 25 %
PE-pellets produced in Finland from industrial/commercial packaging waste, containing labels and tapes (C2)	Can be exempt from registration requirement, according to REACH The conclusion about the content of the substance, triggering classification as hazardous, could not be draw, using described assessment techniques Complies with national product regulations for packaging material Complies with national product regulations for packaging material	Can be processed with conventional extrusion equipment, although addition of 25 % results in unstable bubble in blown film extrusion. Addition of 25% might have a deteriorative effect on mechanical properties of a film produced Use in film applications might be limited by visual properties
PE-pellets, produced outside of Finland from packaging waste (C3)	No assessment could be done regarding compliance with REACH and CLP regulations due to missing information regarding the nature and history of the waste. Complies with national product regulations for packaging material	Can be processed with conventional extrusion equipment Can be used for production of film, at least in ratio of 25 %

6.2. Application for termination of waste status of PE pellets

Polyethylene pellets produced in Finland from transparent industrial/commercial packaging waste, can be considered non-waste, based on the following considerations:

Safety and quality of the pellets

Input waste:

- Input for the recovery process is post-consumer industrial/commercial flexible plastic films collected after functioning as secondary packaging meant to consolidate the retail units on the pallet. The secondary packaging is not in contact with content of the package. The packaging has a short life span and according to EU and national product regulations does not contain more than 100 ppm or mg/kg of lead (Pb), cadmium (Cd), mercury (Hg) and hexavalent chromium (Cr (VI)) in total.
- The flexible plastic packaging is separated by waste producer from other waste at source

- Source separated packaging is transported by the commercial/industrial waste producer to the collection facility in 300 kg bales, where the bales are open, visually inspected and later re-baled.
- Based on the visual examination and hand-NIR identification, plastic packaging material is identified as PE-LD and it does not contain any labels or tapes
- Re-bailed pallets of 500 kg are stored under the roof until delivery to the recycler
- The description of the input waste is available according to standard EN 15347

Recovery process:
- Recovery process includes removal of any accidentally present labels or tapes, pressing of films, shredding and compounding of the material
- The input material collected is kept separately all the time of processing, therefore no contamination with extra materials, including polymers, takes place
- Description of the process is available according to the standard EN 15343

Manufactured pellets:
- Utilizing existing documentation and data obtained at collection/pre-treatment site and conforming it with DSC and FT-IT analysis, at least 80 % of the recycled polyethylene can be shown to be consisting of already registered monomers, eliminating the need for re-registration of the recycled material.
- According to laboratory analysis of a pellet sample, inorganic residue of the material is less than 0.5%. With high probability that does not contain any substance that might trigger its classification as hazardous due to the following considerations:
    - Concentrations of Pb, Cd, Hg and Cr(VI) in input waste is limited by legislation (see “Input waste”)
    - The Information provided on ECHA web site about non-hazardous nature of polyethylene describes that the manufactured material most likely does not trigger classification as hazardous according to CLP.
    - According to scientific literature, transparent polyethylene flexible packaging does not likely to contain any additives or impact-modifiers that contain hazardous substances.
    - Traceability documentation produced according to the standard EN 15343 suggest that no contamination has taken place during the reprocessing or preceding its collection stage.
    - Results of visual examination of the packaging waste performed at the collection facility upon arrival of waste suggest that no contamination was taken place during the use phase either.
- Compliance of packaging and its components with Directive 94/62/EC on Packaging and Packaging waste and Governmental Decree 518/2014 together with traceability documentation, produced according to the standard EN 15343 and supported by data obtained with XRF analysis confirms that pellets produced do not contained any lead (Pb), cadmium (Cd), mercury (Hg) or hexavalent chromium (Cr (VI)), therefore can be used in production of packaging compliant with national and EU regulations.
- At the end of the recycling process the secondary raw material becomes available in free-flowing form with particle size of 3 mm, bulk density of 480-500 kg/m^3 MFR of 0.54 – 1.75 g/10 min, which is in line with size, bulk density and MFR of raw materials used for film extrusion
- Addition of 25 % of the recycled material to the virgin polyethylene does not prevent the blend from being used for film extrusion
- Collection method of input waste ensuring absence of labels and tapes on the packaging has positively contributed to the technical quality of the recyclate

Demand for the pellets

Collection of plastic packaging in EU ad in Finland is facilitated by the fact that the packers of the production are responsible for waste management of the packaging they pack their production in (EPR), therefore the packaging returned to a collection facility should not be subjected to a gate fee.

In order to meet the targets outlined in Directive (EU) 2018/852, by the end of year 2025, 50 % of plastic packaging should be recycled (EPC, 2018), what means that 50% of plastic packaging waste should be collected for recycling, sorted and available for processing. In 2017, 123 kt of PPW were generated in 2017 and 33 kt recovered as material (Vanninen, 2018), i.e. only around 27%. In order to achieve targets, fraction of PPW recycled, i.e. fraction of PPW waste collected and available for recycling, should be doubled, what means that incentives for increased collection with purpose of recycling are required. Termination of waste status for even part of recovered PPW waste would mean more certainty in quality and safety of that recovered waste, improved market and, as result, incentive for collection and sorting of the waste for recycling.

According to Finnish Plastics Recycling Ltd, the market for film-originated recycled PE-LD exists (Suomen Uusiomuovi Oy, 2018, p. 15). If fraction of large films in Finnish PPW is taken equal to Austrian (24% (Van Eygen, et al., 2018)), around 30 kt of mainly PE-LD large film waste could be potentially generated annually. The fraction of these films originating from industry/commerce and collected and available for recycling can be based on estimation by Järvinen and Salminen. According to them, around 9 kt of source separated and collected post-consumer industrial/commercial PE-LD/LLD waste originating mainly from unwrapping of goods is available on the market (Järvinen & Saarinen, 2016).

An average EU cost for processing of PPW is around 850 €/t, an average price of secondary plastic is 650-1000 €/t (Deloitte, 2015). Given the wide range of the price given, a more detailed evaluation would be required in order to calculate the economic incentive of recycling.

Documentation of the process

- All the stages of the collection, pre-treatment and mechanical recycling processes are documented
- References to the internal documentation, detailing the data, personnel and details of the processing and analyzing are not provided in the work, but available at the site, where work was performed
- Description of the process is available according to the standard EN 15343
- At least the following sources of information were used for assessment of the waste status

    - Instructions, according to which the waste was collected
    - Resin Identification Codes
    - NIR-identification
    - Communication with collecting/pre-treatment facility
    - Conformity statement from a producer of the film material in Finland
    - Film-grade PE-LD generic data sheet
    - Standards (SFS- EN 15347, SFS-EN 15343, SFS-EN 15344)
    - Technical guidelines by ECHA (ECHA, 2017) (ECHA, 2010) (ECHA, 2012) (ECHA, 2012)
    - Technical guidelines by Ökopol Institute (Ökopol Institute, 2012)
    - Legislation (PPWD, Governmental Decree 518/2014, REACH, CLP)
    - Scientific literature
    - On-site visual assessment
    - Laboratory analysis
    - Information about quality system of the recycler

- Laboratory analysis included DSC, FT-IR and XRF analysis and measurements of density, tensile and impact properties, ash content and moisture content

6.3. Materials status assessment of pipes-derived PE pellets

The assessment was made in a similar manner, as for first case study. All general comments, for example in related to the standards used in both cases, are omitted to avoid the repetition.

For assessment of compliance with registration requirement under REACH, the collection/pre-treatment facility was interviewed, and information compiled, according to EN 15347 standard, see table 20:

Table 20. *Information, compiled for post-consumer plastic pipe waste, according to standard EN 15347*

Required characteristics	Input material for C4
Batch size	Not defined
Color	Black
Form of waste	Plastic pipes
History of waste	Construction and Demolition waste, pressure pipes
Main polymer present	PE-HD
Other polymers present	None
Packaging	None
Additives, contaminants, moisture, volatiles (optional characteristic)	Dirt and sand, as pipes are stored outside

The information provided by the collection/pre-treatment facility and obtained during the processing of the material was compiled according to the standard EN 15343, see table 21:

Table 21. *Information, compiled according to standard EN 15343 for evaluation of traceability and quality assurance during reprocessing of C4 material*

Data required	Information, collected for input material C4
Origin	
Material type/form	Construction material
Product type	Pipes
Type of waste	Post-consumer waste
Where is it came from	Construction and Demolition activities
History of waste	Plastic PE pipes, identified by marking on the side
Date of collection	During 1-3 month during spring
Logistics	
Collection	Collected mainly within commingled construction and demolition waste, specifically within fraction of recyclables (mainly from new construction sites mixed wood, plastic (except for PVC), cardboard, packaging material, metal) and fraction of mixed waste that is difficult to recycle (containing concrete, minerals, gypsum, insulation fibers, PVC-plastics, glass, bags and pouches, mattresses). Sometimes batches of source separated pipes are delivered to the collection/pre-treatment facility
Sorting	Manual sorting with a small machine equipped with crab, sorting based on black color and PE marking on the surface

Batch size, identification and marking	All pipes separated from commingled construction waste or separately are added to a common batch (pile) over an unspecified time period
Pre-treatment	None
Storage	Outside. Pipes, separated form commingled waste are stored together from source-separated pipes
Analysis before processing	Visual inspection Waste characterization according to EN 15347
Process parameters	Shredded with Untha LR630 shredder with screen size 10 mm and washed with a regular washing machine without chemicals Second shredding into into 3-5 mm pieces with Raptor 15 Series shredder and compounding with twin screw extruded with L/D ratio of 38 at 180-200 ºC at 150 rpm. No substances added during processing.
Analysis after processing	SFS-EN 15344 SFS-EN 13476-3:2018
Intended application	Non-pressure pipe

Material of collected pipes was polyethylene, as only PE-marked pipes were collected. Some commonly used black PE pipes in Finland can be water pressure pipes (plane black or black with blue stripes), gas pressure pipes (plane black or black with orange or yellow stripes) made of PE 80 or PE 100 material or non-pressure drainage pipes (Muoviteollisuus ry, 2012; SFS-EN 13476-3:2018, 2018; EN 12201-2:2011, 2013; EN 1555-2, 2010). Marking on pipes including numbers of 40, 80 or 100 after PE refers to minimum required strength (MRS) of the pipes and signifies that material of the pipe is standardized. PE material used for pressure-pipes is expected to have, among other things, density of ≥ 930 kg/cm^3, 2-2.5% of carbon black and MFR within range of 0.2 – 1.4 g/10 min, as measured at 190 ºC/2.16 kg (EN 1555-2, 2010; EN 12201-2:2011, 2013).

Based on information collected from standards, the material was expected to be PE-HD with carbon black used as a colorant. FT-IR spectrum obtained (see figure 21) was almost identical to a reference PE-HD reference material, except for extra peaks around 2400 – 2300 cm^{-1}, which could be attributed to Carbon Dioxide (NIST, 2018). According to DSC curve, T_m identified as the peak of the endotherm, was 130 ºC, corresponding to T_m of reference virgin PE-HD (see figure 22).

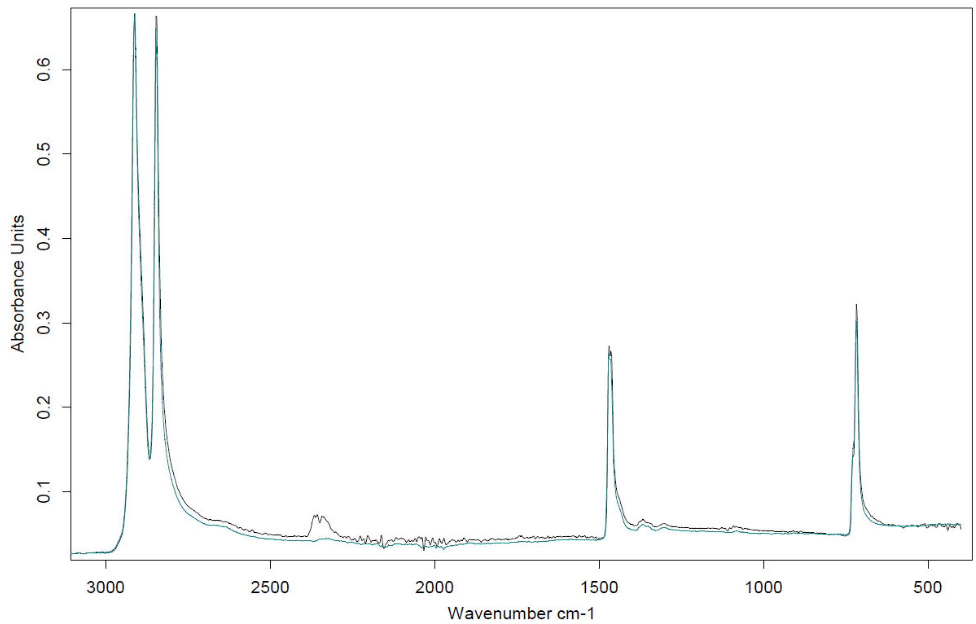

Figure 21. *FT-IR spectrum of EoW candidate C4 (black curve) and reference PE-HD material (green curve)*

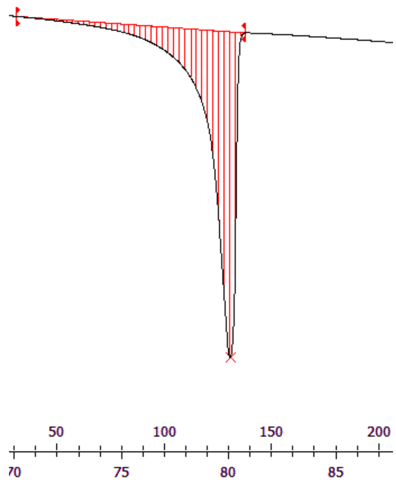

Figure 22. *DSC curve of EoW candidate C4. Upper numbers on the ruler denote temperature.*

Monomer ethylene of the PE-HD polymer constituting the bulk of the material is already registered (CAS no.: 74-85-1, registration can be checked from ECHA web site). Carbon black, a colorant present in concentration 2.3 w% (see table 22) is also registered (CAS no.: 1333-86-4). If the carbon black in the recovered material is deliberately recycled, i.e. its composition and properties are contributing to the final properties of the material, the recovered material is a mixture. Nevertheless, as all deliberately recovered components are already registered, the recovered material does not have to be re-registered. Impurities up to 20% do not need to be registered, what is well above the content of the impurities expected in the recycled pellets (ash content is below 1%, see table 22).

The next step in assessment is evaluation, whether the composition of recyclate can trigger the classification as hazardous according to CLP. According to ECHA web site, neither polyethylene, nor carbon black are classified as hazardous (ECHA, 2018; ECHA, 2018). Inorganic ash residue is < 1% and no problematic elements typically mentioned in product directives are found by XRF (see table 22). According to scientific literature, PE-HD does not usually contain components with hazardous constituents, with possible exception of colorants and fire retardants in electric applications (Hansen, et al., 2013). As black color in the pipes originates from non-hazardous carbon black, the presence of potentially hazardous constituents in manufactured pipes can be considered improbable. Information on traceability compiled according to standard EN 15343 ensures that waste material used as input for C4 has not being in contact with any hazardous substances during or after collection or during the processing and material was washed. Therefore, it is unlikely that any substance triggering classification of the material as hazardous is present in the batch of material analyzed.

Table 22. *Variables, tested to verify compliance of C4 with REACH and CLP requirements*

Variable	**Material C4**
Identity of the main polymer, extraneous polymers (FT-IR, DSC)	PE-HD, T_m 130 ºC, one peak
Ash content	0.08 %; 764 ppm
Carbon black content	2.29 %, 22 943 ppm
Presence of inorganic compounds (XRF)	Ca, Fe, P, Si, Zn, Ti, S

Nevertheless, according to traceability documentation, the input waste was not limited to new construction pipes and, therefore, some old pipes could be the part of the stream. More research would be required to assess nature of the colorants and other property-modifiers used in production of the pipes in the past. Alternatively, composition of the stream can be measured over a prolonged period of time and data analyzed. In the absence of such information for the moment, no conclusion can be made regarding compliance of the whole PE-HD pipe stream with information and communication requirements of PEACH and CLP.

Properties of the recycled PE-HD derived from pipes can be measured according to EN 15344 standard (see table 23).

Table 23. *Information, collected for C4 material according to standard EN 15344*

	Results for C4 and testing method	**Values, provided in TDS for PE80 and testing method**
Characteristics, identified by EN 15344:2007 standard as mandatory and suggested testing method		
Bulk density (annex B to EN 15344)	530 kg/m^3 (ASTM D1895)	Not commonly specified
Color (visual inspection)	Black (visual inspection)	Black (visual inspection)
Particle size and shape (ISO 22498)	Cylindrical small pellets, 3mm length, 85 pellet/g (internal method)	Not commonly specified
MFR (ISO 1133, 190/5)	0.3 g/10 min (ISO 1133)	0.3 g/10 min (ISO 1133)
Characteristics, identified by EN 15344:2007 standard as optional and suggested testing method		
Ash residue (ISO 3451-1)	0.08 %; 764 ppm (ISO 3451-1)	Not commonly specified
Density (ISO 1183-1)	958 kg/m^3 (ISO 1183-1)	956 kg/m^3 (ISO 1183-1)
Moisture content (EN 12099)	140 ppm (ISO 15512)	Not commonly specified
Tensile strain @ break (ISO 527-1 or 2)	532 % (ISO 527-2)	> 600 % (ISO 527-2)
Tensile stress @yield (ISO 527-1 or 2)	23 MPa (ISO 527-2)	22 MPa (ISO 527-2)

The standard EN 15344 only provides the framework for the measurement, but not any requirements for the properties measured, therefore a product standard was required for specifications. Since pressure water and gas pipes standards explicitly prohibit the use of recycled material in the pipes, produced according to these standards, the standard EN 13476-3 for non-pressure pipes was taken as base for evaluation. By that standard, the use of PE-pipes originating recycled material is allowed, if the material satisfies the requirements, provided in the standard (see table 24). As the sample size taken from the collection/pre-treatment facility was only 3 kg, neither a recycler would potentially be capable of manufacturing a pipe on its premises, only material properties that could be tested from pellets were tested. Based on the results of the testing, the EoW candidate C4 could be potentially suitable for use as raw material for non-pressure pipe.

Table 24. *Characteristics, required by non-pressure pipe standard SFS-EN 13476-3:2018*

	Requirement of the standard for recycled material	**Material C4**	**Reference material (TDS value)**
PE content	At least 75 w%	> 80%	Not commonly specified
Density	> 930 kg/m3, test method EN ISO 1183-1	958 kg/m^3	956 kg/m^3
MFR	≤ 1,6 g/10 min, test method EN ISO 1133-1	0.3 g/10 min	0.3 g/10 min
OIT	≥ 20 min, test method EN ISO 11357-6, 200 ºC	83 min (pellet)	> 20 min
Ash residue	≤ 25%, test method EN ISO 3451-1	0.08 %; 764 ppm	Not commonly specified
Extraneous polymers	≤ 5%, test method IR or DSC	None	Not commonly specified
Type of pigment and/or other added substances	Defined by analysis	Carbon black 2.29 %, 22 943 ppm	> 2 %
Total volatiles	≤ 300 mg/kg, test method EN 12099	0.018 %; 177 ppm	Not commonly specified

Evaluation of amounts of secondary PE-HD originating from C&D waste

In study by Ronkanen around 15 % of mixed C&D waste was plastic (Ronkanen, 2016). In Finland around 1.5 – 1.8 Mt of house C&D waste was produced (Laaksonen, et al., 2017), of which 40% was wood, 31% minerals and 14% metal (Salmenperä, et al., 2015). An assumption can be made that composition of mixed C&D waste handled by collection/pre-treatment facilities of C&D waste roughly corresponds to composition of house construction/demolition/renovation waste with excluded fractions of concrete, wood and metal, usually collected separately (see discussion in section 5.2 regarding study of composition of C&D waste). Using that assumption, the amount of plastic in C&D waste can be estimated to be 34 – 41 kt/a:

$$Amount\ of\ plastic\ in\ \ C\&D\ waste, estimation\ 1\ \left(\frac{kt}{a}\right) =$$
$$Amount\ of\ house\ construction\ waste\ (Finland, 2017) * (1 - fraction\ of\ metal -$$
$$fraction\ of\ concrete - fraction\ of\ wood) * fraction\ of\ plastic\ in\ mixed\ C\&D\ waste$$
$$1\ 500\ kt * (1 - 0.14 - 0.4 - 0.31) * 0.15 = 34\ kt/a$$

On the other hand, in EU in 2012 the fraction of plastic from C&D waste to PPW was around 9.5% (see distribution of plastic waste by source in 4.1.1). Using that fraction for Finland, where 117-123 kt/a of PPW is generated, C&D waste could generate 11-12 kt of plastic waste (see calculations below):

$$Amount\ of\ plastic\ in\ \ C\&D\ waste, estimation\ 2\ \left(\frac{kt}{a}\right)$$
$$= Amount\ of\ PPW\ (Finland, 2015) * \frac{Amount\ of\ plastics\ in\ C\&D\ waste\ (EU, 2012)}{Amount\ of\ PPW\ (EU, 2012)}$$
$$117\ kt * \frac{1512\ kt}{15876\ kt} = 11\ kt/a$$

As in both estimations certain assumptions are used, the range of 10 – 40 kt/a of plastic in C&D waste can be used for the following calculations. That amount is below the amounts suggested by Sahimaa & Dahlbo (68-122 kt (Sahimaa & Dahlbo, 2017)), but within the interval suggested by Eskelinen et al. (20-220 kt/a (Eskelinen, et al., 2016)).

According to report by Deloitte, in EU in 2012 on average 25% of plastic from C&D waste was sent to recycling (i.e. collected and sorted for recycling). According to the same report, at the output of the sorting process, a fraction of PE-HD in C&D plastic was 12%, as most of C&D plastics was PVC (see (Deloitte, 2015) and sections 4.1.3 - 4.1.4 of this work). In study by Ronkanen, around 30 % of C&D plastic was hard plastic, excluding PVC and PS (Ronkanen, 2016). If we re-calculate the fraction of PE-HD in C&D plastic, provided by Deloitte report in reference to plastics excluding PVC, then also on average in EU PE-HD would constitute around 30% of C&D plastics after excluded PVC.

Using the data above, roughly 0.75 – 3 kt/a of PE-HD could be available for recycling from C&D waste (see calculations for 10 kt/a as starting point below):

$$Amount\ of\ PE-HD\ available\ available\ on\ , estimation\ \left(\frac{kt}{a}\right)$$
$$= Amount\ of\ plastic\ in\ \ C\&D\ waste\ in\ Finland * \eta_{collection\ and\ sorting}\ (EU)$$
$$* Fraction\ of\ PE-HD\ in\ sorted\ plastic$$
$$10\ kt/a * 0.25 * 0.3 * 0.74 = 0.75\ kt/a$$

These numbers are in line with real-life observations. During the collection trial in Finland in 1999-2011 maximum of 150 t/a of plastic pipe residues were collected.

Calculation of PE-HD available in C&D waste are based on series of assumptions, resulting in high degree of uncertainty related to estimation.

Summary

Based on the assessment provided above, polyethylene pellets, produced by extrusion from PE pipes collected in Finland from C&D waste, might **NOT** be considered non-waste, as <u>despite that</u>

1. PE-HD is commonly used for production of plastic pipes
2. In EU demand for recycled PE-HD in construction sector is higher than in packaging, automotive and electronic sector - Amount of PPW-based secondary polyolefins used in construction sector in EU is highest, comparing to other sections (see figure 6 for details), implying existence of demand for recycled PE-HD in construction sector. Data on C&D-plastic waste originated PE demand in construction is not yet available.
3. The stream of pipes is composed of relatively large products with clear markings on the sides, which can be used for identification of material and attribution to a standard used for the production.
4. Recycled PE-HD produced from waste PE pipes fulfills the technical requirements defined in standard EN 13476-3 for non-pressure pipes. The material produced can be exempt from registration requirement according to REACH.

The following considerations might prevent the termination of pellets waste status:

4. Estimated amount of PE-HD in C&D waste stream is relatively small, although the result of the estimation might vary significantly, if based on more recent data and/or refined assumptions.
5. The information requirement within CLP regulation and communication requirement within REACH and CLP cannot be satisfied, as the identity of additives and property-

modifiers used in the production of the pipes produced since 1960s could not be established within the present study.

In order to comply with information requirement, the author recommends the following actions:

- Until more information on composition of pipe waste is available, input waste could be limited only to residues of new pipes produced in construction activities (excluding demolition and renovation activities for the moment)
- The survey of additives and property-modifiers, used in pipe production in 1960-2018, can be undertaken together with review of standards and legislation, relevant to plastic pipes in the same period
- A study of composition of pipe waste stream originating from C&D waste could be undertaken, producing a probability of presence of potentially hazardous substances in the stream.

6.4. Discussion

Termination of the waste status of a selected material stream was demonstrated through evaluation of the information collected about recyclate against criterial developed during preparation stage of the work and documentation of the whole process.

Preparation work for assessment consisted of documentation review, selection of EoW candidate material streams from the initial waste stream, mapping the sufficient processing steps, choosing the criteria against which the chosen recovery system was evaluated and performing laboratory analysis of the selected waste material streams and recovered material.

The spectra of documents reviewed was exceptionally wide. It included both waste and product-related legislative texts, technical guidelines, scientific reports, articles and studies concerning the composition of recycled plastics, technical information on capabilities of analytical methods and standards.

In the present work, the EoW candidate material streams were already chosen for the author. Nevertheless, for other similar undertakings, the literature reviewed suggests that the choice is important, as part of the original waste stream might have properties that prevent it from becoming non-waste. Termination of waste status is usually possible for some applications of some of the outputs, not for initial waste stream and all its outputs.

Establishing the extent of the recovery process for the assessment was another significant part of the assessment preparation. For packaging case study, the input waste was assumed to be inspected and identified, while recovery process was assumed to start with sorting and washing of the packaging at the recycling facility. The division was based on division of activities performed by the collection/pre-treatment facility and by the recycling facility. If the recycling facility would be receiving the source-separated bales directly from the waste producer, the extent of the recovery process would be different.

A challenging step in the preparation work was choosing the criteria, against which the recovered material was evaluated. In absence of EU wide or national EoW criteria for waste plastics, the criteria were chosen based on general guidelines outlined in EU waste legislation, ECHA technical guidelines and published guidelines from EU countries, where practice of material status assessment is more common. The criteria chosen were based on legal pre-requisites described in the section 3.1. They encircled technical performance and safety of recyclate and included compliance with requirements imposed by REACH and CLP regulation, product regulation and product standards, where available. Existing standards for recyclate characterization were utilized as a backbone for information collection, although they did not provide any guidelines on specifications required from the recyclate for waste status termination. Particularly the standard EN 15343 proved to be very useful as a backbone for collection of information during the collection/pre-treatment of waste and recycling process.

The actual waste status assessment consisted of comparing the information regarding composition and recovery processes of the industrial/commercial post-consumer packaging and post-consumer PE-HD pipe waste from C&D waste to the criteria established in the preparation step. The needed information was collected using standards discovered in the preparation step as a backbone, by interviewing the collection/pre-treatment facilities' personnel, by reviewing the regulations, standards and other information sources mentioned in the section 4.2.2 for virgin plastics and by laboratory analysis. For assessment of packaging-derived EoW candidates packaging-related regulations provided the limitations on some hazardous components in the packaging waste input material, while standards for pressure and non-pressure pipes could be used for evaluation of composition and technical characteristics of the pipe waste input material. Simple and fast analytical methods with easily interpretable results were used for laboratory analysis, as sophisticated lab equipment and substantial material knowledge, was assumed to not always be available for an average recycler. The analysis alone would not be sufficient to establish the conformity with mentioned criteria, but it served as a good support tool in the assessment.

From requirements assessed within the present study, especially information requirement according to REACH and CLP prompt the producer to be aware of even low (< 1%) concentrations of constituents present in the recyclate. During polyolefin product life such materials as additives, property-modifiers, other polymers or non-polymers from layered structures, labels and tapes, printing inks, adhesives and substances added during reprocessing can become part of the recycled polymer. The transparent packaging-derived recyclate without labels, tapes and ink was the most likely candidate to obtain the non-waste status, as information regarding composition of the material stream was concentrated at a few points of the value chain – manufacturer of the polymer and collection facility. Absence or scattering of information regarding the origin of the input material to the recovery process (C3) or nature or composition of the components of the input (C2 and C4) made the assessment impossible mostly due to the information requirement.

Markets for produced recyclates were described for EU and for Finland assessed only at a general level. In EU demand exist for packaging derived recycled polyolefins, especially in construction sector. The case studies were limited to packaging and pipe-derived post-consumer polyolefins. The information related to the composition of these streams can be used for the similar assessments, if material streams and recovery process assessed are the same. The result of the assessment is also valid only for the specified material streams and recovery process. If another material status assessment would be made for another waste-derived polyolefin by another author, the approach, documentation reviewed, and details presented in the assessment might vary in the absence of common methodology.

Demonstration of the termination of the waste status of Finnish post-consumer polyolefin waste required extensive literature survey, interview with participants in the supply chain and consulting by both material science and chemical- and waste legislation experts. Eight months of full-time work was required from the author. Existing national methodology for material status assessment of waste plastic would significantly assist the task and development of the methodology is on its' way in 2019.

In identification of the waste, potentially hazardous nature of the waste is an important feature, as waste can be associated with risks to health or environment. Evaluation of safety of recovered waste is one of the key points in assessment, whether waste status of material can be terminated. It is also the reason, why showing that recovered material complies with only technical requirements for some application is not sufficient.

Recovered plastic waste with terminated waste status - a recycled plastic - can be used by the plastic converter in similar ways as raw material originating from virgin stock. The fact that material is non-waste does not automatically mean, that it is of high quality, in the same way as being virgin material does not automatically mean the ultimate quality of the stock. Instead, it means that the user of the material can expect certain similar features from the waste-derived material, as from virgin raw material, including traceability and safety.

The main benefit of waste status assessment is increased level of knowledge about recycled material. Increase level of knowledge can be utilized for tailoring material properties of the recycled material, for transparent and open communication with material users regarding material characteristics, for more accurate predictions of material behavior and, as result, higher demand for the material and better understanding of properties of recycled plastics amount industrial users and common public.

Some recommendations can be made as a result of the assessment. Information availability plays a decisive role in the waste status assessment, therefore collaboration of actors in the plastic product value chain and common terms and definitions are required. Common terms should encircle all stages of plastic product life from polymer production to conversion to use and discarding and reprocessing. Differences in definitions observable in chemical and waste legislation and terminology used by virgin material manufacturer and recyclers lead to difficulties in communication.

EPR scheme for packaging resulted in development of such system as Grüne Punkt in Germany and later in other EU countries. That, in turn, resulted in development of common specifications and consequently predictable properties of plastic packaging waste, serving as input for recycling. For now, in Finland, the specifications for waste plastic packaging should be derived from guidelines provided by the collection/pre-treatment facilities. Development of common packaging plastic waste classes with common for the whole country specifications would improve predictability of the properties of the input waste for recycling.

Design for recyclability guidelines provide the designers and manufacturers of a product with such instructions as material choices. Certification bodies ensure the compliance with the guidelines and compatibility of a product with local recycling system. Certified products therefore constitute a desired input to the recycling process and certificates of the products can be used in assessment of material status of the waste, generated by it. In Finland guidelines for recyclability exist for packaging, but certification is not available at present.

7. CONCLUSIONS

This Master's Thesis work strives to answer the question "How termination of waste status of polyolefins in Finland can be demonstrated?". Termination of the waste status can be demonstrated through evaluation of the information collected about recyclate against developed criteria and documentation of the whole process.

Preparation for the assessment is resource consuming. The challenging steps in the preparation is establishing system boundaries and criteria against which the assessment is done. In assessment itself, the evaluation of conformity of the recovered material with chosen criteria requires communication with waste supplier and plastic manufacturer, careful analysis of available documentation and selection of suitable analytical methods. For successful demonstration of waste status termination, available and created documentation is extremely important. Especial attention must be given to documentation, related to any substances, initially present or added during lifetime or recovery process of discarded plastic items.

Assessment of material status and demonstrated terminated waste status result in increased level of knowledge regarding properties of the recovered material, availability of information regarding its safety and certain degree of predictability of the properties. Such knowledge is expected to result in the higher industrial demand for the recyclate. In the future, optimization of the assessment process would be required for introduction and wider use of the assessment by the recyclers and improved availability of the secondary polyolefins on Finnish market.

The challenging nature of the work performed highlighted the need for development of national methodology for material status assessment for waste plastics, collaboration of actors in the supply chain and enhanced communication assisted by common terminology. Additionally, development of common specifications or waste classes, for example by EPR organization, is encouraged to improve predictability of the properties of the plastic waste, used as input for recycling process. Another development suggested is certification of adherence to design-for-recyclability guidelines, which ensures the compatibility of the product with existing recycling schemes already at the design stage.

REFERENCES

Aaltonen, L.-K., 2014. *Teknisten muovien kierrätys, DI-työ.* Tampere: TTY.

Amerplast, 2018. *Herätä kuluttajan huomio kestävillä tuotteilla.* [Online] Available at: http://www.amerplast.com/kaupan_kassit_ja_pakkaukset/?lang=fi [Accessed 14 8 2018].

APC, 1997. *Understanding plastic film: Its uses, benefits and waste managemnt options,* s.l.: American Plastics Council.

APM, 2017. *Association of European Plastics Manufacturers - Plastics - the Facts 2017.* [Online] Available at: https://www.plasticseurope.org/application/files/5715/1717/4180/Plastics_the_facts_2017_FINAL_for_website_one_page.pdf [Accessed 17 7 2018].

APM, 2018. *Association of European Plastic Manufacturers - Who we are.* [Online] Available at: https://www.plasticseurope.org/en/about-us/who-we-are [Accessed 18 7 2018].

APM, 2018. *Association of European Plastics Manufacturers - Plastics in Packaging.* [Online] Available at: https://www.plasticseurope.org/en/about-plastics/packaging [Accessed 12 12 2018].

Auvinen, S., 2018. *Conversion and packaging, MOL-72106 course slides.* Tampere: TUT.

BIO, 2011. *European Comission DG ENV: PLASTIC WASTE IN THE ENVIRONMENT,* EU: Bio Intelligence Service.

Borealis Media Release, 2016. *Borealis acquires German recyclers mtm plastics GmbH and mtm compact GmbH.* Vienna: Borealis.

Borealis Media Release, 2018. *Borealis to acquire Austrian plastics recycling company Ecoplast Kunststoffrecycling GmbH.* Vienna: Borealis.

Borealis, 2018. *Polyolefins.* [Online] Available at: https://www.borealisgroup.com/polyolefins [Accessed 12 6 2018].

Brinston, H. F. & Brinston, C. L., 2008. Characteristics, Applications and Properties of Polymers. In: *Polymer Engineering Science and Viscoelasticity.* Boston, MA: Springer, pp. 55-97.

Brouwer, M. T. et al., 2017. Predictive model for the Dutch post-consumer plastic packaging recycling system and implications for the circular economy. *Waste Management,* Volume 71, pp. 62-85.

Butler, T. I. & Morris, B. A., 2012. PE-based multilayer film structures. In: *Plastic Films in Food Packaging.* ebook: William Andrew, pp. 21-50.

CEN/TR 15353, 2007. *Plastics. Recycled Plastics. Guidelines for the development of standrads for recycled plastics..* online: SFS.

CEN, 2018. *European Committee of Standardization: What is a Standard.* [Online] Available at: https://www.cen.eu/work/ENdev/whatisEN/Pages/default.aspx [Accessed 3 7 2018].

Christensen, T. H., 2010. Construction and Demolition Waste. In: T. Christensen, ed. *Solid Waste Technology and Management.* Ebook: John Wiley & Sons,, pp. 104-110.

Christensen, T. H., 2010. Industrial Waste. In: Christensen, ed. *Solid waste technology and Management.* UK: Blackwell Publishing Ltd, pp. 100-103.

Christensen, T. H. & Fruergaard, T., 2010. Commercial and Institutional Waste. In: T. Christensen, ed. *Solid Waste Technology & Management.* Electronic: John Wiley & Sons,, pp. 97-100.

Christensen, T. H., Fruergaard, T. & Matsufuji, Y., 2010. Residential waste. In: T. Christensen, ed. *Solid Waste Technology and Management.* s.l.:John Wiley & Sons,, pp. 85-97.

Debergh, P., Acoleyen, M. v. & Nelen, D., 2015. *Analysis of certain waste streams and the potential of Industrial Symbiosis to promote waste as a resource for EU Industry – Final report,* Brussels: European Commission.

Delgado, C., Barruetabeña, L. & Salas, O., 2007. *Assesment of the environmnetal advantages and drawbacks of existing and emergening polymer recovery processes,* Spain: JRC.

Deloitte, 2015. *Increased EU Plastics Recycling Targets: Environmental, Economic and Social Impact Assessment,* France: Plastics Reyclers Europe.

Deloitte, 2017. *Blueprint for plastic packaging waste: Quality sorting and recycling,* France: Plastic Recyclers Europe.

DerGrunePunkt, 2017. *EPR for Packaging in Germany - Der Grune Punkt.* Oslo: Green Dot Norway Conference.

Destaclean, 2018. *Lajitteluohjeet 1.6.2018 lähtien.* [Online]
Available at: http://188.64.4.14/materaalien-lajittelu-ja-vastaanottoehdot/
[Accessed 15 8 2018].

Dixon, N. et al., 2010. Chapter 5: Waste Charactreization. In: D. Zekkos, ed. *Geotechnical Characterization, Field Measurement, and Laboratory Testing of Municipal Solid Waste.* USA: American Society of Civil Engineers, pp. 135-205.

ECHA, 2010. *Guidance on waste and recovered substances, version 2.* Helsinki: ECHA.

ECHA, 2012. *Guidance for monomers and polymers,* Helsinki: ECHA.

ECHA, 2012. *Guidance on information requirements and chemical safety assesment, version 2.1.* Helsinki: ECHA.

ECHA, 2017. *Guidance for identification and naming of substances under REACH and CLP,* Helsinki: ECHA.

ECHA, 2018. *Substance information, carbon black, CAS no 1333-86-4.* Helsinki: ECHA.

ECHA, 2018. *Substance information: Ethene, homopolymer (CAS no 9002-88-4).* [Online]
Available at: https://echa.europa.eu/substance-information/-/substanceinfo/100.121.698
[Accessed 5 12 2018].

ECHA, continiously updated. *Guidance on REACH.* [Online]
Available at: https://echa.europa.eu/web/guest/guidance-documents/guidance-on-reach
[Accessed 29 8 2018].

EEA, 2018. *Heavy metal emissions.* [Online]
Available at: https://www.eea.europa.eu/data-and-maps/indicators/eea32-heavy-metal-hm-emissions-1/assessment-9
[Accessed 19 10 2018].

Ellen MacArthur foundation, 2016. *The New Plastic Economy - Rethinking the future of plastics,* eReport: World Economic Forum.

Emblem, A., 2012. Packaging functions. In: A. Emblem & H. Emblem, eds. *Packaging technology.* UK: Woodhead Publishing Limited, pp. 24 - 60.

EN 12201-2:2011, 2013. *Plastic piping system for water supply, and for drainage and sewage under pressure - Polyethylene (PE) - Part 2: Pipes.* Brussels: CEN.

EN 1555-2, 2010. *Plastic piping system for the supply of gaseous fuels - Polyethylene (PE) - Part 2: Pipes.* Brussels: CEN.

Environmental Agency (UK), 2016. *Guidance - Non-packaging plastics: quality protocol.* [Online]
Available at: https://www.gov.uk/government/publications/non-packaging-plastics-quality-protocol/non-packaging-plastics-quality-protocol
[Accessed 29 10 2018].

EPC, 1994. European Parliament and Council Directive 94/62/EC of 20 December 1994 on packaging and packaging waste. *Official Journal ,* Volume L 365, p. 10.

EPC, 2000. *Directive 2000/53/EC of European Parliament and of Council of 18 September 2000 on end-of-life vechicles.* Brussel: EU.

EPC, 2002. REGULATION (EC) No 2150/2002 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 25 November 2002 on waste staistics. *Official Journal of the European Communities,* 9 12, L 332(9/12), pp. 1-36.

EPC, 2004. Regulation (EC) No. 850/2004 of the European Parliament and of the Council on persistent organic pollutants and amending Directive 79/117/EEC. *Official Journal of the European Union,* L 158(7).

EPC, 2006. REGULATION (EC) No 1907/2006 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency [...]. *Official Journal of the European Union,* Volume 49, p. L 396.

EPC, 2006. Regulation (EC) No 1907/2006 of the European Parliament and the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency [...]. *Official Journal,* Volume L 396, p. 1.

EPC, 2008. *Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives.* s.l.:s.n.

EPC, 2008. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. *Official Journal of the European Union,* 22 11, 51(L312), pp. 3-30.

EPC, 2011. Directive 2011/65/EU of the European Parliament and of the Council of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment. *Official Journal of the European Union,* 174(88).

EPC, 2012. *Directive 2012/19/EU of the European Parliament and the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE).* Brussels: EU.

EPC, 2015. *Directive 94/62/EC of European parliament and of Council of 20 December 1994 on packaging and packaging waste.* Brussels: EPC.

EPC, 2018. *DIRECTIVE (EU) 2018/851 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 30 May 2018 amending Directive 2008/98/EC on waste.* eDocument: EC.

EPC, 2018. *Directive (EU) 2018/852 [...] amending Directive 94/62/EC on packaging and packaging waste.* s.l.:EPC.

EPRO, 2017. *Plastic packaging waste statistics 2016.* [Online]
Available at: http://www.epro-plasticsrecycling.org/pages/75/epro_statistics
[Accessed 20 9 2018].

Eriksen, M., Pivnenko, K., Olsson, M. & Astrup, T., 2018. Contamination in plastic recycling: influence of metals on the quality of reprocessed plastics. *Waste management,* Volume 79, pp. 595-606.

ESFA, 2015. *European Food Safety Authority - Plastics and plastic recycling.* [Online]
Available at: https://www.efsa.europa.eu/en/topics/topic/plastics-and-plastic-recycling
[Accessed 27 8 2018].

ESFA, E. F. S. A., 2008. General principles on safety assesment of recycled plastics intended to be used for manufacture of maetrials and articles in contact with food. *The ESFA Journal,* Volume 717, pp. 4-12.

Eskelinen, H., Haavisto, T., Salmenperä, H. & Dahlbo, H., 2016. *Muovien kierrätyksen tilanne ja haasteet,* Helsinki: Clic.

Essi kiertokassi, 2018. *Usein kysytyt kysymykset.* [Online]
Available at: https://www.kiertokassi.fi/artikkeli/usein-kysytyt-kysymykset/
[Accessed 21 8 2018].

EU Science Hub, 2018. *Raw Materials Information System (RMIS), Policies and Definitions.* [Online]
Available at: http://rmis.jrc.ec.europa.eu/?page=policies-and-definitions-2d5b5e
[Accessed 16 6 2018].

EuCerPlast, 2018. *Download key documents.* [Online]
Available at: https://docs.wixstatic.com/ugd/dda42a_35f229306557479fb26f4b798e8cf66b.pdf
[Accessed 27 8 2018].

European Comission, 2000. Commission Decision of 3 May 2000 replacing Decision 94/3/EC establishing a list of wastes [...]. *Official Journal of European Union,* 3 5, Volume 226, p. 3.

European Comission, 2005. *COM(2005) 666 final: COMMUNICATION FROM THE COMMISSION [..]: Taking sustainable use of resources forward: A Thematic Strategy on the prevention and recycling of wa.* Brussels: Comission of European Communities.

European Comission, 2008. Comission Regulation N 282/2008 on recycled plastic materials and articles intended to come into contact with foods and ammending Regulation (EC) No 2023/2006. *Official Journal of the European Union,* 86(9), pp. 9-18.

European Comission, 2010. COMMISSION REGULATION (EU) No 849/2010 of 27 September 2010 amending Regulation (EC) No 2150/2002 of the European Parliament and of the Council on waste statistics. *Official Journal of European Union,* 28 9.L 253(2).

European Comission, 2012. *Guidance on the interpretation of key provisions of Directive 2008/98/EC on waste.* s.l.:EC.

European Comission, 2014. *Final Report Summary - W2PLASTICS (Magnetic Sorting and Ultrasound Sensor Technologies for Production of High Purity Secondary Polyolefins from Waste),* Brussels: European Comission.

European Comission, 2018. *COM (2018) 32 final - Communication [...] on the implementation of the circular economy package:options to address the interface between chemical, product and waste legislation.* Strasbourg: EC.

European Comission, 2018. *COM(2018) 28 final: Communication from the commission to the European Parliament, the Council, The European economic and social committee and the committee of the regions: A European Strategy for Plastics in a Circular Economy.* Brussels: European Commission.

European Comission, 2018. Commission notice on technical guidance on the classification of waste. *Official Journal of the European Union,* 2018/C(124/01).

European Comission, 2018. *Environment: Waste Framework Directive.* [Online]
Available at: http://ec.europa.eu/environment/waste/framework/end_of_waste.htm
[Accessed 19 7 2018].

European Comission, 2018. *Growth - Internal market, Industry; Enterpreneurship and SMEs-CE marking.* [Online]
Available at: https://ec.europa.eu/growth/single-market/ce-marking_en
[Accessed 4 7 2018].

European Comission, 2018. *Single-use plastics: New EU rules to reduce marine litter.* [Online]
Available at: http://europa.eu/rapid/press-release_MEMO-18-3909_en.htm
[Accessed 6 12 2018].

European Communities, 2000. Commission Decision of 3 May 2000 [...] establishing a list of wastes [...] 2000/532/EC. *Official Journal of the European Communities,* 3 5, 43(L 226), pp. 3-25.

Eurostat, 2010. *Guidance on classification of waste according to EWC-Stat categories (version 2); Supplement to the Manual for the Implementation of the Regulation (EC) No 2150/2002 on Waste Statistics.* [Online]
Available at: http://ec.europa.eu/eurostat/documents/342366/351806/Guidance-on-EWCStat-categories-2010.pdf/0e7cd3fc-c05c-47a7-818f-1c2421e55604
[Accessed 6 6 2018].

Eurostat, 2015. *Raw materials.* [Online]
Available at: http://ec.europa.eu/eurostat/web/environmental-data-centre-on-natural-resources-old/natural-resources/raw-materials
[Accessed 10 7 2018].

Eurostat, 2017. *Recycling – secondary material price indicator.* [Online]
Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Recycling_%E2%80%93_secondary_material_price_indicator
[Accessed 20 9 2018].

FINLEX, 2011. *646/2011 Jätelaki (Finnish Waste Act).* Helsinki: Finlex.

FINLEX, 2012. *Valtioneuvoston asetus jätteestä (Governmental Decree on waste) 19.4.2012/179.* Helsinki: Finlex.

FINLEX, 2013. *Valtioneuvoston asetus kaatopaikoista 331/2013.* Helsinki: Finlex.

FINLEX, 2014. *Valtioneuvoston asetus pakkauksista ja pakkausjätteistä 518/2014.* [Online]
Available at:
https://www.finlex.fi/fi/laki/alkup/2014/20140518?search%5Btype%5D=pika&search%5Bpika%5D=518%2F2014
[Accessed 28 8 2018].

Fortum, 2018. *Suomalaisten kannattaa kerätä muovipakkaukset kierrätykseen.* [Online]
Available at: https://www.fortum.fi/media/2018/07/suomalaisten-kannattaa-kerata-muovipakkaukset-kierratykseen
[Accessed 14 8 2018].

Gálvez-Martos, J.-L., Styles, D., Schoenberger, H. & Zeschmar-Lahl, B., 2018. Construction and demolition waste best management practice in Europe. *Recources, Conservation and Recycling,* Volume 136, pp. 166-178.

Hansen, E., Nilson, N. H., Lithner, D. & Lassen, C., 2013. *Hazardous substances in plastic materials,* Velje: COWI.

Hiipakka, M., 2011. *Muovien kierrätys, DI-työ.* Tampere: TTY.

Hiljanen, M., 2014. *Kierrätysmuovien modifiointi, DI-työ.* Tampere: TTY.

Hopewell, J., Dvorak, R. & Kosior, E., 2009. Plastic recycling: challenges and oportunities. *Phil. Trans. R. Soc. B,* 2009(364), pp. 2115-2126.

Hu, B. et al., 2013. Recycling-oriented characterization of polyolefin packaging waste. *Waste Managment,* 33(3), pp. 574-584.

Hundertmark, T., McNally, C., Simons, T. J. & Vanthournout, H., 2018. *McKinsey&Company - No time to waste: What plastics recycling could offer.* [Online]

Available at: https://www.mckinsey.com/industries/chemicals/our-insights/no-time-to-waste-what-plastics-recycling-could-offer?cid=soc-web
[Accessed 1 10 2018].
Institute cyclos - HTP, 2017. *Verification and examination of recyclability,* Aachen: Institute cyclos.
Ipsos Mori, 2018. *Public concern about plastic and packaging waste is not backed up by willingness to act.* [Online]
Available at: https://www.ipsos.com/ipsos-mori/en-uk/public-concern-about-plastic-and-packaging-waste-not-backed-willingness-act
[Accessed 6 12 2018].
ISO 14021:2016, 2016. *Environmental labels and declarations. Self-declared environmental claims (Type II environmental labelling).* Helsinki: SFS.
ISO 18236-2, 2015. *Plastics - Mixtures of polypropylene (PP) and polyethylene (PE) recyclate derived from PP and PE used for flexible and rigid consumer packaging- Part 2: Preparation of test specimens and determination of the properties.* Geneva: ISO.
ISO 18263-1, 2015. *Plastics - Mixtures of polypropylene (PP) and polyethylene (PE) recyclate derived from PP and PE used for flexible and rigid consumer packaging- Part 1: Designation system and basis for specifications.* Geneva: ISO.
ISO 9000, 2005. *Quality management systems. Fundamentals and vocabulary.* Helsinki: SFS.
ISRI, 2018. *Scrap Specifications Circular 2018.* Washington DC: ISRI.
Jambeck, J. R., Roland Geyer, C. W. T. R. S. & al, e., 2015. Plastic waste inputs from land into the ocean. *Science Research reports,* 347(6223), pp. 768-771.
Järvelä, P. & Järvelä, P., 2015. *Teknisten muovien kierrätys ja uusiokäyttö,* Lahti/Tampere: LAMK/TTY.
Järvinen, P. & Saarinen, E., 2016. *Muovien kierrätys ja hyötykäyttö Suomessq.* Porvoo: Bookwell Oy.
Karlsson, S., 2004. Recycled Polyolefins. Material properties and means for quality determination. *Advanced Polymer Science,* Volume 169, pp. 201-229.
Kauppila, J. et al., 2018. *Jätteeksi luokittelun päättymisen hyödyt ja haitat; YMPÄRISTÖMINISTERIÖN RAPORTTEJA 9/2018,* helsinki: Ympäristöministeriö.
Kneck, S., 2018. *Conversation.* Porvoo: s.n.
Korpivaara, A., Kess, J. & Marjut Mäntynen, e. a., 2013. *Rakentamisen materiaalitehokkuuden edistamisohjelma,* Helsinki: Ympäristöministeriö.
La Mantila, F. P., 1996. *Basic Concepts on the recycling of Homogenous and heterogenous Plastics.* Palermo, ChemTec Publishing.
Laaksonen, J., Merilehto, K., Pietarinen, A. & Salmenperä, H., 2017. *Valtakunnallinen jätesuunnitelma vuoteen 2023,* Helsinki: Ympäristöministeriö.
Lagerkvist, A., Ecke, H. & Christensen, T., 2010. Waste Charactreisation: Approaches and Methods. In: T. Christensen, ed. *Solid Waste Technology and Management.* s.l.:John Wiley and Sons, pp. 63-84.
Lehtonen, S., Wiik, C., Nurmi, V. & Koivuniemi, M., 2015. *Loppuraportti: orgaanisia epäpuhtauksia sisältävien teollisten kalvomuovien pesukokeilu ja kierrätysprosessin kehitys,* Riihimäki: Ekokem Oy.
Luijsterburg, B. & Goossens, H., 2014. Assesment of plastic packaging waste: material origin, methods, properties. *Resources, concervation and recycling,* Volume 85, pp. 88-97.
Mehmood, S., Khaliq, A. & Ranjha, S., 2010. *The use of post consumer plastic waste for the production of wood plastic composites: A Review.* Venice, Third International Symposium on Energy from Biomass and Waste.
Merikarvia-lehti, 2017. *Muoviportti tarvitsee lisää tilaa – kaava ei este.* [Online]
Available at: https://www.merikarvialehti.fi/uutiset/muoviportti-tarvitsee-lisaa-tilaa-kaava-ei-este-200412050/
[Accessed 5 10 2018].
Merta, E. et al., 2012. *Muovipakkausten kierrätyksen edistäminen Suomessa, TEM raportteja 11/12,* Helsinki: Työ- ja elinkeinoministerio.
Muoviteollisuus ry, 2009. Muoviputket Ympäristölle kestävä ratkaisu. *Putkijaoston julkaisu no 38*.
Muoviteollisuus ry, 2012. Paineputkijärjestelmät polyeteenista (PE). *Putkijaoston julkaisu no 42*, 24 08.

Muoviteollisuus ry, 2018. *Putkijaosto - CE-merkintä ja NPM merkki.* [Online]
Available at: https://www.plastics.fi/fin/organisaatio/putkijaosto/ce-merkinta_ja_npm-merkki/
[Accessed 16 7 2018].

Muoviteollisyys ry, 2018. *Muovitieto.* [Online]
Available at: http://www.plastics.fi/fin/muovitieto/muovit/
[Accessed 24 8 2018].

Mylläri, V. et al., 2016. Detergent impurity effect on recycled HDPE: Properties after repetitive processing. *Journal of Applied Polymer Science,* 133(31).

NIST, 2018. *NIST Chemistry WebBook, SRD 69, Infrared Spectrum of Carbon Dioxide.* USA: NIST.

NPM, 2018. *Nordic Polymark.* [Online]
Available at: http://nordicpolymark.com/
[Accessed 23 10 2018].

Obermeier, T. & Lehmann, S., 2017. *New Calculation Method for Measurement of Recycling Rates and Influence on Recycling Quotas,* s.l.: European Academy.

OECD, 2010. *OECD Global Forum on Environmnet, focusing on sustainable materials management. Materials Case Study 4: Plastics,* Mechelen: OECD.

OECD, 2018. *Improving markets for recycled plastics - Trends, Prospects and Policy responses,* Online: OECD.

Ökopol Institute, 2012. *Ökopol Institute fur Ökologie und Politik GmbH: REACH and the recycling of plastics. Reference manual for an appropriateimplementation of the REACH requirements for the operators of recycling plants.* Hamburg: Umweltbundesamt (Federal Environmnetal Agency, Germany).

Orthex group, 2017. *Kuluttajien kierrättämä uusiomuovi käyttöön Lohjan tehtaalla.* [Online]
Available at: http://www.orthexgroup.fi/inspiroidu/orthex---ekokem-yhteistyo
[Accessed 21 8 2018].

Oxford Reference, 2017. *A Dictionary of Environmnet and Conservation, 3nd edition.* s.l.:Oxford University Press.

Palkopoulou, S. et al., 2016. Critical review on challenge test to demonstrate decontamination of polyolefins intended for food contact application. *Trends in Food Science and technology,* Volume 49, pp. 110-120.

PCE, 2018. *SDS-R Tool Service.* [Online]
Available at: https://polymercomplyeurope.eu/pce-services/sds-r-tool-service
[Accessed 5 12 2018].

Pekki, L. & Liski, U.-M., 2017. *Vahanen - Jätepuun tuotteistaminen edistää kierrättämistä.* [Online]
Available at: https://vahanen.com/fi/vahanen/ajankohtaista/jatepuun-tuotteistaminen-edistaa-kierrattamista/
[Accessed 16 7 2018].

Pirkanmaan ELY-keskus, 2017. *Ympäristö.fi.* [Online]
Available at: http://www.ymparisto.fi/download/noname/%7BC68C61B1-E9B0-46F4-BE13-D4359943C586%7D/119813
[Accessed 10 8 2018].

Plastic Pipe Institute, 2008. *Pars Ethylene Kish Co., Handbook of PE pipe.* [Online]
Available at: http://www.parsethylene-kish.com/separsekish/default.aspx?page=Document&app=Documents&docId=11895&docParId=11460
[Accessed 14 12 2018].

Plastic Recyclers Europe, 2017. *PRE Downloads - Design for recycling guidelines - PE transparent Natural Flexible films guidelines.* [Online]
Available at: https://plasticsrecyclers.eu/downloads
[Accessed 17 12 2018].

Plastics Recyclers Europe, 2018. *Glossary.* [Online]
Available at: http://www.plasticsrecyclers.eu/glossary
[Accessed 18 7 2018].

Plastics Recyclers Europe, 2018. *Starting page.* [Online]
Available at: https://www.plasticsrecyclers.eu/
[Accessed 2 10 2018].

Poropudas, M., 2011. *Polyvinyylikloriidin (PVC) kierrätys ja uusiokäyttö, diplomityö,* tampere: TTY.

PRO Europe, 2018. *The Green Dot Trademark.* Brussels: PRO Europe.

Ragaert, K., Delva, L. & Geemb, K. V., 2017. Mechanical and chemical recycling of solid plastic waste. *Waste Management,* Issue 69, pp. 24-58.

Riley, A., 2012. Basic of polymer chemistry for packaging materials. In: A. E. &. h. Emblem, ed. *Packaging technology.* s.l.:Woodhead Publishing Limited, pp. 262 - 287.

Rinki, 2018. *Pakkausten uudelleenkäyttö syö jätemäärää.* [Online]
Available at: https://info.rinkiin.fi/pakkausten-uudelleenkaytto-syo-jatemaaraa/
[Accessed 6 12 2018].

Ronkanen, M., 2016. *Rakennus- ja purkujätemateriaalin lajittelun kehittäminen.* Lappeenranta: LUT.

Ronkanen, M., 2018. *E-mail communication.* Helsinki: s.n.

Sahimaa, O. & Dahlbo, H., 2017. *Material flow analysis of plastic for Finland.* [Online]
Available at:
http://arvifinalreport.fi/files/Material%20flow%20analysis%20of%20plastic%20for%20Finland%20160117.pdf
[Accessed 25 5 2018].

Salmenperä, H., Moliis, K. & Nevala, S.-m., 2015. *Jätemäärien ennakointi vuoteen 2030,* Helsinki: Ympäristöministeriö.

Salmenperä, H. et al., 2016. *Kohdennetut keinot kierrätyksen kasvuun,* Helsinki: Valtioneuvoston selvitys- ja tutkimustoiminnan julkaisusarja 53/2016.

Salminen, J., 2018. *Ryhmäpäällikkö, SYKE, e-mail conversation.* Porvoo: s.n.

SFS 5884:2018, 2018. *Betonimurskeen maarakennuskäytön laadunvalvontajärjestelmä.* Helsinki: SFS.

SFS EN 15347, 2007. *Plastics. recycled Plastics. Characterization of plastic wastes.* Helsinki: SFS.

SFS, 2018. *Finnish Standards Association: Relationship between standards and other publications.* [Online]
Available at:
https://www.sfs.fi/en/publications_and_services/getting_to_know_standards/relationship_between_standards_and_other_publications
[Accessed 3 7 2018].

SFS-EN 13430, 2004. *Packaging. Requirements for packaging recoverable by material recycling.* Helsinki: SFS.

SFS-EN 13476-3:2018, 2018. *Plastics piping systems for non-pressure underground drainage and sewerage. Structured-wall piping systems of PVC-U, PP and PE. Part 3: Specifications for pipes and fittings with smooth internal and profiled external surface and the system, Type B.* Helisnki: SFS.

SFS-EN 15343, 2007. *Plastics. Recycled Plastics. Plastics recycling traceability and assessment of conformity and recycled content.* Helsinki: SFS.

SFS-EN 15344, 2007. *Plastics. Recycled Plastics. Characterisation of Polyethylene (PE) recyclates.* Helsinki: SFS.

SFS-EN 1852-1:2018, 2018. *Plastics piping systems for non-pressure underground drainage and sewerage. Polypropylene (PP). Part 1:Specifications for pipes, fittings and the system.* s.l.:SFS.

SFS-EN ISO 17855-1, 2014. *Plastics. Polyethylene (PE) moulding and extrusion materials. Part 1: designation system and basis for specifications.* Helsinki: SFS.

Sorum, L., Fossum, M., Evensen, E. & Hustad, J. E., 1997. *Heavy Metal Partitioning in a Municipal Solid Waste Incinerator.* USA, Proceedings of fifth annual North American waste-to-energy conference; PB: 1102 p.

Suez, 2017. *Press Release - SUEZ and Lyondellbasell to boost production of high-quality recycled plastics in Europe.* Worldwide: Suez.

Suomen Uusiomuovi Oy, 2015. *Yritysten muovipakkauksia? Toimi näin.* Helsinki: Suomen Uusiomuovi Oy.

Suomen Uusiomuovi Oy, 2018. *Muovikassissa on yli 90 prosenttia kierrätysmuovia.* [Online]
Available at:
http://www.uusiomuovi.fi/fin/muovi_kiertaa/yritysesimerkkeja/amerplast_ent_suominen_joustopakkaukset/
[Accessed 14 8 2018].

Suomen Uusiomuovi Oy, 2018. *Opas kierrätyskelpoisen muovipakkauksen suunniteluun,* Helsinki: Taitto Kiriprintti Oy.

Suomen virallinen tilasto (SVT), 2016. *Jätetilasto [verkkojulkaisu]. ISSN=1798-3339.* [Online]
Available at: http://www.stat.fi/til/jate/2016/jate_2016_2018-08-31_tie_001_fi.html
[Accessed 10 12 2018].

Thoden Van Velzen, U., 2015. *Post-consumer plastic packaging waste recycling systems in the Netherlands (presentation).* Hamburg: ISWA.

Van Eygen, E., Laner, D. & Feller, J., 2018. Circular economy of plastic packaging: Current practice and perspective in Austria. *Waste Managment,* Volume 72, pp. 55-64.

Vanninen, S., 2018. Muovipakkausten keräys uuteen ennätykseen. *Uusimaa*, 6 8, p. 8.

Vesilind, P. A., 2003. Chapter 14 - Reuse, Recycling and Resource Recovery. In: R. M. Ruth Weioner, ed. *Environmental Engineering.* s.l.:Elsevier, pp. 273-294.

Villanueva, A. et al., 2010. *Study on the selection of waste streams for end-of-waste assessment,* Seville: JRC.

Villanueva, A. & Eder, P., 2014. *JRC Technical Reports: End-of-waste criteria for waste plastic for comversion,* Luxembourg: Publications Office of the European Union.

Worrell, E., 2014. Recycling of packaging. In: *Handbook of Recycling.* Electronic: Elsevier Inc., pp. 297 - 307.

Wu, X., Chen, J. & Zeng, X., 1991. The application of DSC in identification of LDPE/LLDPE blends mulching film. *Die Angewandte Makrornolekulare Chemie,* 189(3197), pp. 183-193.

Yle, 2018. *Verkkokaupan muovit sotkevat kierrätystä.* [Online]
Available at: https://yle.fi/uutiset/3-10208404
[Accessed 14 8 2018].

Ympäristö.fi, 2018. *Jätehuollon vastuut ja järjestäminen.* [Online]
Available at: http://www.ymparisto.fi/fi-FI/Kulutus_ja_tuotanto/Jatteet_ja_jatehuolto/Jatehuollon_vastuut_ja_jarjestaminen
[Accessed 15 6 2018].

YTP liitto, 2017. *Circular economy examples.* [Online]
Available at: http://www.ytpliitto.fi/fin/ajankohtaista/kiertotalousesimerkkeja/
[Accessed 14 8 2018].

APPENDIX A

An example of specifications for fraction N 310 of Plastic films used in Germany. The specifications are constructed to represent the quality of material traded in the industry (Villanueva & Eder, 2014).

Parameter	Specifications
Restrictions on the input	The system compatibility of a piece of packaging, also in respect of the product filled in it, is a prerequisite for licencing and will be checked by an expert as required. Basically, only unground products from the sorting process of light weigh packaging arising from household collection system that are operated by contract partners of the Duales System Deutschland (DSD) GmbH are excepted.
Description of the material	Use, completely emptied, system-compatible articles made of plastic film, surface > DIN A4, i.e. bags, carrier bags and shrink-wrapping film, including packaging parts such as labels
Purity of the material	At least 92 w% in accordance with description of the material above
Impurities	Max total amount of impurities: 8 w% Metallic and mineral impurities with an item weight of > 100 g are not permitted Other metal articles: < 0.5 w% Other plastic articles: < 4 w% Examples of impurities: glass, paper and cardboard, composite paper/cardboard materials (i.e. beverage cartons), aluminised plastics, other materials (e.g. rubber, stones, wood, textiles, nappies), compostable waste (e.g. food, garden waste)
Bale specifications	Dimensions and density of the bales must be chosen so as to ensure that a tarpaulin truck (loading area 12.6 m * 2.4 ; lateral loading height min 2.6 m) can be loaded with a min loading of 23 t
Other specifications /guidelines	Dry-stored Produced with conventional bale presses Identified with DSD bale label stating the sorting plant No., fraction No., and production date