Accepted Manuscript

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PII: S0304-3894(19)30840-4
DOI: https://doi.org/10.1016/j.jhazmat.2019.120887
Article Number: 120887

Reference: HAZMAT 120887

To appear in: *Journal of Hazardous Materials*

Received date: 26 February 2019
Revised date: 17 June 2019
Accepted date: 9 July 2019

An overview of the challenges and trade-offs in closing the loop of post-consumer plastic waste (PCPW): Focus on recycling

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Graphical abstract

Highlights

- Plastic waste recycling is currently facing a wide range of bottlenecks.
- There is a need for a sufficient collection, sorting and recycling infrastructure.
- Mechanical and aesthetic properties of the recyclates should be carefully considered.
- Potential collaboration within industries may be proved a fruitful route.
- A combined and aligned effort by all involved parties is a necessity.

Abstract

Recycling of post-consumer plastic waste (PCPW) is increasingly promoted as the way to achieve circular economy (CE), by converting plastic waste into secondary materials that can be fed back into the system, for use in the same or in new components and products, with similar or lower functionality; hence "closing the loop". Up until today, research on examining the environmental impacts, economic implications and technicalities of plastic waste recycling deals only with one particular aspect, or stage on the plastic value chain, lacking coherence and structure. To move this research forward, understanding the challenges and trade-offs in scaling up plastic waste recycling is necessary. Here, we bring together existing literature on the multi-faceted aspects of closing the plastic loop, critically debating on the multi-stakeholder endeavours of promoting circularity in plastics. We present an overview of how design, production, collection and sorting of PCPW present challenges for its recycling, which in turn result to a number of trade-offs. We explain that the evaluation of the multi-dimensional implications of trade-offs, arising from the PCPW recycling, is essential in measuring the long-term sustainability of such systems. This work scrutinises the sustainability of closing the plastic waste loops and sets a future research agenda.

Keywords: plastics; plastic waste; closing the loop; circular economy; limitations and barriers;

ABBREVIATIONS

approx.	Approximately
CE	Circular economy
CVORR	Complex value optimization for resource recovery

EU	European Union
HDPE	High-density polyethylene
LAs	Local authorities
MCPs	Materials, components and products
MRF	Material recovery facilities
NIR	Near infrared
PCPW	Post-consumer plastic waste
PET	Polyethylene terephthalate
PRFs	Plastic recovery facilities
R&D	Research and development
SuPs	Single-use plastics

1. Introduction

Circular economy (CE) is gaining global momentum. Its core idea of moving away from the current linear 'take-make-use-dispose' economy to one that is restorative and regenerative by design has been embraced by governments around the world [1-5]. There is now an abundance of definitions to describe CE [6, 7]. Our own interpretation is that CE is '*a system that has the ability to restore, retain and redistribute materials, components and products (MCPs) in the best possible way and for as long as it is environmentally, technically, socially and economically feasible*'. This stipulates a fundamental reconsideration of resource producing, consuming and recovering systems [8-11].

In our view, achieving CE is a global ambition, with regional variations. There is no one size-fits-all approach to its implementation. Consequently, local and national governments must come up with their own plans and frameworks for adopting the CE taking into account regional specificities, governance and organisational structures. In some cases, a complete revamping of the system might be needed. In the European Union (EU), this approach is increasingly embraced by both industry and policy spheres, as evident by the CE Action Plan [12], and the newly revised EU waste legislation and Directives which demonstrate EU's commitment to promote sustainable management of its resources [13-15].

Better management of our resources entails better management of their embedded environmental (e.g. water, energy), economic (e.g. costs of design, manufacture and distribution), social (e.g. labour intensity), and technical (e.g. additives used to make a component or product stronger, colour, labels, coatings, etc.) values, and delays their wastage. Wastage of resources entails costs, i.e. via dissipation of embedded values and often the creation of negative values and other externalities [11]. Ultimately, all types of value stem from technical value; the set of inherent, designed and created characteristics that render an MCP useful in the first place [11, 16]. The weathering of these properties through the use and poor management of MCPs may reduce their technical value to the point that waste is created and 'costs' in the social, environmental and economic domains occur.

Plastics, are a great example of MCPs of which technical value is largely destroyed in our current systems [16, 17]. This creates a swirl of negative impacts to the environment, society and economy, as evident by the large amounts of post-consumer plastic waste (PCPW) that is littered and/or is lying unexploited in the landfills and open dumpsites around the world, polluting our terrestrial and marine environment [18]. According to recent estimates, 4900 Mt of the 6300 Mt total of plastics ever produced have been discarded either in landfills or elsewhere in the environment, and only 567 Mt (9%) have been recycled [19].

A growing number of international agreements (e.g. UNEA-3) [20], EU policies and strategies (e.g. the Strategy for Plastics in a CE) [21], legislative initiatives on single-use plastics (SUPs), and voluntary agreements (e.g. UK Plastics Pact) [22], are calling for action in adopting better waste management measures and increasing recycled plastics demand [23]. This has placed increased focus on improving PCPW recycling rates. Years of research on the environmental performance of plastic waste management (e.g. landfilling, incineration), have shown that recycling results in net energy savings [24, 25], leads to a net reduction in the emission of CO_2, carbon monoxide, acid gases, particulate matter, heavy metals and dioxins [26-28], and contributes less to acidification effects, nitrification of surface water [27, 28] and human toxicity [29].

Life Cycle Assessment (LCA), has been widely used in assessing the environmental performance of plastic waste recycling (focusing on a particular polymer type or mixed plastic) owing to its ability to include the collection, sorting, and reprocessing phases [24-35]. The need to consider economic and social values accrued by the plastic waste recycling process, has led to combinations of environmental analyses with economic [27, 36-40], and social valuations [41]. These analyses, focused predominantly at the environmental feasibility and financial viability of the recycling process, looking at the impact of different regional collection schemes, segregation methods in the household, and the quality of the plastic waste material sorted, neglecting to account for wider systemic aspects [42].

While environmental and economic aspects are important in assessing the sustainability of PCPW recycling, these are often the only aspects used to inform decision-making processes. This limited view encourages recycling in promoting CE, to the exclusion of sustainability, which bears the risk of creating problems to new points in the plastic value chain [43]. The recycling of PCPW is a complex process. It depends upon the numerous stages that precede it (e.g. production, distribution, use, disposal and sorting), the many stakeholders involved, and the political (e.g. taxation, incentives) and organisational structures (e.g. plastic waste collection schemes, financial structures, and supply-demand dynamics) of the system in which it is practiced. The literature that addresses this complexity is scarce [16, 44-48], and often incomplete.

Here we revisit the concept of closing the PCPW loop and debate critically the multi-stakeholder endeavours in promoting the circularity of the PCPW [16]. Drawing on evidence from emerging literature on the technical feasibility of plastic waste recycling, we provide an overview of how the design and production of plastics and the collection and sorting of PCPW present a number of challenges for its recycling, which in turn give rise to trade-offs. Our objective is to place emphasis on the need to understand the positive and negative value creation and externalities of recycling PCPW for capturing unwanted knock-on effects that will impact the long-term sustainability of our systems. With this analysis we seek to contribute to the debate of scaling up the PCPW recycling option as the way forward in promoting CE.

2. Recycling of plastic waste: the basics

Plastic recycling is the process of recovering and reprocessing waste plastic into a new (secondary) material that can be used in the production of new components and products. There are four plastic waste recycling processes: i) primary recycling (re-extrusion); ii) secondary recycling; iii) tertiary recycling (chemical or feedstock recycling); and iv) quaternary recycling (energy recovery), a description of which can be found elsewhere [49, 50]. Primary recycling is only used for the management of pre-consumer (also known as post-industrial) plastic waste (e.g. fall-out components/products, cuttings, trimmings), due to the high level of homogeneity required; the rest of the recycling processes are commonly used for the treatment of PCPW.

In this article we focus on secondary recycling, also known as *mechanical recycling or plastics reprocessing*. It is one of the most well-established and widely used methods of plastic waste recycling [51-56]. It includes the collection, sorting and pre-treatment, decontamination and reprocessing of sorted types of PCPW [56] into a secondary raw material for new products [57]. At global level, the mechanical recycling rate of plastic waste is thought to be between 14 and 18% [58]. The rest of the plastic waste is managed via energy recovery (24%), or is disposed of in landfill or the natural environment (58 - 62%) [59]. Generally, the proportion of PCPW that is recycled varies from one region to another, with Europe ranking third best in recycling [60], with a 31% recycling rate [61]. According to Ragaert et al. [48] the largest share of PCPW is packaging waste [48]. In Europe, the recycling rate of packaging waste (40.8%) exceeds that of energy recovery by 2% [62].

Mechanical recycling is distinguished into closed- and open-loop recycling, based on the quality of the secondary material produced. In closed-loop recycling, also known as 'upcycling', the recycled material is of equal or comparable quality to the original product. As a result the recycled material is used in the production of the same products as before, substituting an amount of virgin material (e.g. PET bottles into new PET bottles) [17].

In open-loop recycling, also known as 'downcycling', the quality of recycled material may be lower than that of its original product, due to erosion of the plastic properties. In this case the recycled material cannot be used in the production of the original product and in other, usually lower quality, applications (e.g. PET bottles into fleece or printer components) [17]. This type of recycling is a form of "cascading". Where degradation of plastic material properties occurs, "cascading" is considered the optimal option for recovering plastic material value [11]. However, this does not necessarily imply that the new product is of lower 'value'. For example, a PET bottle turned into a PET bottle will become waste in less than a year leading to a wastage of all embedded values, whereas bottle turned into products such as fibres for pillows, printers, car parts can extend the time that the new product spends in the system, delaying as such the time all embedded values become 'waste' [17].

The concept of cascading is depicted in Fig. 1. As illustrated in Fig.1, in cascading we have a sequential use of materials, of which quality continues to degrade over successive lifecycles, until it becomes too low for the materials to be used any further [63, 64]. In this cascade recycling system, a resource does not necessarily follow a "one-way" street and in many a cases, intermediate products cannot be further recycled. The majority of PCPW enters into a cascade recycling system, whereas closed-loop recycling accounts for only a small portion of all plastics recycled [65].

Generally, sorted plastic waste must be of good quality to be accepted for reprocessing. Quality, as explained in our previous work is one of the greatest challenges in promoting the mechanical recycling of PCPW [16, 17]. A number of factors are influencing the quality of PCPW and hampering progress towards a CE [16, 17]. These include: application (e.g. packaging, food-contact, automotive, etc.), type of polymer, multiplicity of collection schemes, additives and others materials (e.g. inks, coatings, adhesives, caps labels) added on the polymer and fate thereof, impurities introduced (e.g. dirt, organic residues, dust, and soil) and degradation during the polymer's service life (and over successive uses).

In promoting the circularity of PCPW based on sustainability principles, we need to understand the way the above factors affect the efficiency of the mechanical recycling process and the ability of the system to return the polymer back to an appropriate quality. Some of the emerging challenges facing the proponents of mechanical recycling process seeking to close the PCPW loop are schematically depicted in Fig. 2. These are discussed in detail in the following section.

3. Challenges and trade-offs in upscaling plastics recycling process

A number of stages precede the mechanical reprocessing of PCPW. These are the: design, production, use/ handling, separation at source (i.e. industry, public sector, consumers), disposal, collection and sorting. Each stage creates implications in the mechanical recycling process, and must be taken into account when assessing the sustainability of the PCPW recycling. Here, we focus on the collection, sorting and reprocessing, as well on the design and production processes. The use/handling and separation/disposal stages are excluded from our analysis. It is our view that these two areas require special consideration, as consumers play a critical role in PCPW recycling. Their purchasing decisions, perceptions, behaviour and attitudes towards the use and disposal of plastics, carry many implications for PCPW recycling and the environment, economy and human well-being. Nonetheless, implications of these stages in the wider system may be implied in our broader analysis.

3.1 Collection and sorting

The collection and sorting of plastic waste are processes with regional variations, supported by a diverse infrastructure that varies greatly amongst regions, countries and cultures [66]. While in the Global North plastic waste management is supported by a formal collection system and advanced waste management infrastructure, in many countries in the Global South recycling of plastic waste is often uncontrolled or underdeveloped, with miniscule environmental and human protection enforced [67, 68]. In informal recycling contexts, collection of plastic waste is not systematic and is often implemented by informal networks. The activities of the informal recycling sector are largely reliant on trade prices and demand for specific plastic types (mostly PET, HDPE and PP), which may fluctuate both over the course of the year and between locations. This results in significant fractions of plastic waste left uncollected, polluting the environment and creating a missed opportunity for their recycling.

In the Global North plastics are often collected at kerbside, but household waste recycling centres (also known as ‘civic amenity sites’), and bring sites/banks may also support their collection. Kerbside is a commonly used option, where the collection of plastics takes place in containers (mostly boxes, bags or sacks); either mixed with other dry recyclable materials (e.g. metals, card, glass) or collected separately [47]. There is a variety of kerbside collection schemes implemented around the world and may involve the collection of mono-plastic (one polymer type, e.g. PET, HDPE) streams or mixed plastic streams. Usually all PCPW is mixed together and the resulting polymer mix may include high value streams such as PET, PE, PP mixed with PVC (e.g. cosmetic packaging, inflatable pools), PS (e.g. egg trays, plastic cups, yoghurt pots), and small fractions of other polymers such as polycarbonate (PC), acrylonitrile butadiene styrene (ABS) and polyamide (PA) [48, 62].

The versatility and frequency of collection schemes currently implemented by local authorities (LAs) or municipalities around the world is another constraint to increasing the mechanical recycling of plastic waste [47, 69, 70]. While this may not be immediately perceived as a challenge, with people moving around constantly due to employment and other activities, differences in the collection systems can create confusion. This compromises the ability of people to dispose their plastic waste in the correct bin, which in turn compromises the quality of the resultant plastic waste streams. In addition, businesses that have the responsibility of placing plastic MCP in the wrong recycling receptacles are often not well aware on how to do this properly [16, 17, 47]. This has a direct impact on the sorting process.

The sorting process may take place in a material recovery facility (MRF), a plastic recovery facility (PRF), a sorting centre and/or in a reprocessing facility, depending on the context (i.e., developed vs developing country) and the source of plastic waste (e.g. consumer, commercial, construction). Sorting is a critical factor in the recycling of plastic waste, because it controls the material that is going to be transported (in bales) to reprocessors within the same or different regions or countries. It can be a step of its own, but also in combination with collection, which depends on the infrastructure that is in place and vice versa, and reprocessing. The latter is an additional step to retain the quality of the high value plastic waste streams that are to be recycled.

Sorting can be performed via automated machinery, as well as manually. In technologically advanced facilities, near infrared (NIR) technology is used. This optical surface technique is the most widely used method for the automated sorting of plastics but involves a number of limitations. The sensor ‘reads’ what it ‘sees’; and the sensor is blind to “carbon black” [71, 72]. This implies that false readings may often occur as the sensor detects a label made of PP instead of the bottle made of PET, or a tray made of PP which may include multiple layers of other materials including non-polymers (i.e. multilayer plastics). Carbon-black pigments confound the spectroscopic scanners used to sort plastic materials, and the sensor cannot ‘read’ the material, e.g. black PET, leading to its rejection [71].

For this reason NIR technologies are often coupled with different physical based sorting machines for plastics such as the sink-float process or hydro-cyclone process [73], or even manual sorting, to ensure that high purity levels can be achieved especially for high value plastics e.g., clear polyethylene terephthalate (PET) and high density polyethylene (HDPE). However, in less advanced facilities the sorting process can be less efficient resulting in a rejection of target plastic waste materials of approx. 13% to 18% [47]. This is in addition to other losses due to non-target plastic waste materials that are discarded, which account for another 12% to 15%. In informal contexts, sorting is largely dictated by the personnel, equipment and space available in addition to the selling price and the buyers with which they trade.

Sorting is largely affected by the composition of PCPW. Mixed PCPW streams may include multi-layered plastics, flexible plastics (i.e. films and bags), black plastics and bio-based plastics that are currently non-NIR identifiable and thus not recycled [48]. Plastic films account for a considerable fraction of plastic packaging waste, which in developed countries is between 40-50% of PCPW. Plastic films have the potential to be recycled, but their low bulk density causes technical issues during the conventional recycling processes making them uneconomic for sorting and mechanical reprocessing [74, 75]. Similarly, multilayer plastic components are difficult to recycle due to the lack of economically viable systems for segregating the various materials they are made of [76]. Accordingly the presence of these components in the sorting process is a sign of potential contamination as they may end up in the single polymer streams [77-79].

Compostable and oxo-degradable plastics are designed to break down rather than be recycled, and their intrusion into the conventional plastic waste streams can compromise the quality of the resulting recycled plastic. Other, bio-based plastics, such as bio-PE and bio-PET, which are identical to their petrochemical-based counterparts and can be used in exactly the same applications (called ‘drop-in’ materials), can be easily integrated into the existing system. This implies that bio-PE and bio-PET can be recycled together with their conventional counterparts (e.g. bio-PE in the PE-stream or bio-PET in the PET-stream), which maximises the recovery of their value [80-82].

Polylactic acid (PLA) can also be recycled. Mechanical recycling of PLA is considered the best valorisation option for PLA from an environmental point of view. This is because it reduces the consumption of raw materials; hence it lowers demand for arable land and contributes lees to carbon emissions and energy consumption [83, 84]. At present this material is not properly sorted for mechanical recycling. It requires the adaption of the existing equipment in the sorting and reprocessing facilities to introduce a new stream line for PLA. The economic feasibility of doing so based on supply-demand dynamics currently hampers development in this area. Therefore, the presence of PLA in the PCPW can contaminate the high-value plastic waste streams (e.g. PET, HDPE), affecting their recyclability [16].

In the study of Beltran et al. [83] it was reported that PLA can be degraded during its service life and the mechanical recycling can deteriorate further its key properties (e.g., viscosity, thermal stability and mechanical properties) [83]. Karamanlioglu et al. [85] reported that PLA although biodegradable, it presents a high risk of environmental contamination due to its stability in terrestrial and aquatic environments at ambient temperatures [85]. Dedicated commercial composting facilities with controlled temperatures can reduce this risk. Nonetheless, the future and sustainability of PLA is highly uncertain.

Labels and sleeves often cover more than 60% of the plastic component. This may also lead to errors in the identification of the polymer type by the sorting equipment. If the sleeve is made by a different polymer type than of the component it is wrapped on, it will either be rejected (if made by a polymer that is not sorted) or end up in another polymer's stream (if made by a polymer that is sorted). This results in cross-contamination of the plastic waste streams [72]. If the sleeve is made from the same polymer as the components it is wrapped on, it will lower its quality, especially if the sleeve is coloured [72].

Other factors at the sorting stage that may impede the efficiency of the mechanical recycling process, include the storage time of recyclates (i.e. raw material sent to, and processed in, a waste recycling plant or materials recovery facility) before sorting, types of materials mixed with plastic waste (e.g. glass, paper, metals), and the waste flow on the conveyor belt.

3.2 Sorting and mechanical reprocessing of plastic waste

Effective recycling requires an effective separation of plastic waste from the other material streams [86]. To achieve that, mechanical recycling process consists of a number of steps to ensure good quality material at the end of the process. First, sorted plastic waste goes through a dry treatment process where they are cut into small flakes. This process aids the decontamination of flakes; a process that removes other types of material or impurities, such as dirt, adhesives, labels and other residues, via a cyclone. Usually, losses at this stage are approximately 20% [73]. After decontamination, the plastic flakes are further processed based on their physical and chemical properties to meet defined quality criteria. Separation based on their density (by the use of floating), grain size (milling process), dirt and residual moisture (via caustic wash for removing any persistent contaminants and glues, and drying) occurs, and then the plastic flakes are re-melted. In this reprocessing stage additives are added into the plastic melt, which is then extruded to strands and pelletized to produce a single-polymer. The granulates are water-cooled and finally sold [56]. Detailed description of this process can be found elsewhere [48, 50].

In practice, when plastics enter the reprocessing stage, a number of mechanisms take place. Plastic waste materials undergo mechanical (i.e. shear forces effects) and thermal (i.e. high temperature effect) degradation during the melting and extrusion process leading to thermal-mechanical degradation [17, 56, 87-89]. Both mechanisms occur simultaneously during the reprocessing stage. Thermal-mechanical degradation can cause chain scission and chain branching that affect the characteristics of the polymer and cause the release of low-molecular volatile compounds. The release of low-molecular volatile compounds from the polymers implies changes to their molecular structure, which in turn affects their rheological and mechanical behaviour [17, 56, 87-89]. The changes in the mechanical properties (e.g. elongation at break, impact strength) are polymer dependent ranging from considerable reductions to small changes. Thermal (e.g. melting temperature, crystallisation) and physical (e.g. colour and surface) properties are also affected, but these effects can be lessened by the addition of different additives (e.g. heat stabilisers, fillers, pigments, caustic soda) [48].

The composition of polymers, their designed and created attributes, partial degradation during their service life, sorting efficiency, and manifestation of their designed and created attributes also come into play during reprocessing, determining to a large extend the success of the recycling process. Polymers may degrade during their service life, due to exposure in certain environmental conditions such as heat, oxygen, light, ionic radiation, moisture and mechanical shear [48]. Mechanical recycling can deteriorate this degradation, lowing the quality of the resultant material.

Contamination induced by the designed (e.g. labels, adhesives, additives) and created (e.g. dust, organic residues, soil) attributes at the collection, sorting and recycling of plastic waste streams (e.g. PET, PE, PP), can complicate or severely affect polymers reprocessing [97, 98]. Designed contamination (i.e. contaminants) can be grouped into: i) designed contaminants that are embedded in the plastics, e.g., additives, coatings, inks [90, 91]; and ii) designed contaminants that are non-embedded (attached) to the plastics, e.g., caps, adhesives and labels (can be plastic and non-plastic materials). Created contamination (i.e. impurities) can be grouped into: i) created contamination at the use/handling and collection, e.g., dust, soil, organic residues, grease, etc.; and ii) created contamination at the sorting stage, e.g., by non-targeted polymeric material in the sorted plastic waste streams (e.g. PET with PVC or PLA) [17].

Contaminants may not always be completely removed at the washing stage, complicating the process of mechanical recycling. For example:

- Coating and inks (designed contamination) can affect the gloss of the final product and can restrict the use of recyclates to certain applications (i.e. when a matte finish is required) [72, 92];
- Additives (e.g. phthalates) (designed contamination) used during plastic manufacturing, but also present in labels and adhesives used on the final product, can persist in the recycling process, resulting in the spreading and accumulation in the recycled polymer [93];
- Aluminium residues (could both designed and created contamination) can be converted into aluminium hydroxide (by the action of caustic wash during

reprocessing) which contaminates the recycled material and prevents its suitability as a food grade material (in the case of PET) [72].

- Mixed PCPW collection and sorting increases the risk of cross-contamination (created contamination) of one polymer by another (e.g. PVC with PET) which can cause changes in the recycled polymers structure and release substances that may cause damage (e.g. corrosion) to the reprocessing equipment [72, 92, 94, 95].

In Table 1, we present the challenges associated with the mechanical reprocessing of PCPW, as construed based on our understanding of the system. We provide a short description of these challenges and their associated trade-offs. In the trade-offs we often refer to positive and negative value creation, and externalities.

Positive value creation refers to the potential increase in employment due to decentralisation and increases in recycling activities, decrease in fossil fuel dependence, reduction in resources (e.g. land, energy, water, chemicals) and pollution induced by other treatment options (e.g. landfill and incineration) due to preference in recycling, as well as net economic savings achieved by the recycling process. With negative value creation we may refer to the: disruption of plastics circularity potential; rejection of recycled plastics and disposal to landfill which leads to dissipation of all values embedded in them (e.g. energy and water consumption, chemical compounds used, embodied emissions, labour, costs involved, etc.); negative net energy and cost savings from the recycling process; safety concerns associated with the use recycled plastics content; and other ex-post environmental, economic, technical and social impacts arising by the distribution and use of recycled plastic content. With negative externalities we refer to the transformation of something with a positive value (reprocessing of PCPW into a stable secondary material) into something that involves a significant cost (e.g. damages to the reprocessing equipment, bias towards the recycling of black plastic waste, restrictions in the sale of secondary plastic material, and so on).

As shown in Table 1, the majority of challenges presented is associated with decisions made upstream of the system, at the design/production and use stage. Plastics are rarely used in their pure polymeric form. Polymers are usually mixed with additives such as plasticizers, flame retardants, antioxidants, acid scavengers, light and heat stabilizers, lubricants, pigments, antistatic agents, slip compounds and thermal stabilizer [89]. These additives can create implications during the mechanical reprocessing of PCPW. There is very little information regarding the presence, behaviour and fate of additives during the reprocessing stage [25].

Lack of information regarding the chemical composition of additives (some of which can be potentially hazardous) used in different plastic waste fractions and their fate during reprocessing, can delimit the displacement of virgin plastics with recycled ones [69, 71]. Increasing the recycled plastic content is also hampered by the lack of information on the mechanical properties, colour limitations, as well as on several other technical challenges involved. Manufacturers find it easier and safer to design products using virgin plastics, safeguarding that the right strength and properties for a specific application are attained [71]. In general, the recycled plastic content of a certain plastic product needs to be assessed on a case by case basis, as the quality specification are often product specific.

The trade-offs associated with the mechanical recycling challenges have far reaching consequences, affecting the sustainability of the entire plastic value-chain, and effectively the circularity potential of PCPW. To that end, it is clear that for the plastic value chain to come full circle, a multi-dimensional valuation of recycling is required and the concept of 'design out the plastic waste' needs to be revisited and reconsidered. Complex-value optimisation for resource recovery (CVORR), a novel, multi-dimensional valuation approach that goes beyond conventional methods of estimating value [103], can aid the multi-dimensional valuation of PCPW recycling.

CVORR combines scientific and engineering methods with a socio-political narrative in assessing resource recovery from waste systems, and connects bottom-up and top-down approaches in identifying and measuring multi-dimensional value (i.e. environmental, economic, social and technical positive and negative impacts) [104]. It can address systemic challenges through transparency and flexibility, while accounting for the dynamic and non-linear nature of commodities flow and the interdependencies and trade-offs between different structures and processes. This approach highlights key areas of concern (where negative value is created), and opportunities (where value is captured or positive value is created) generating insights on system dynamics and creating sustainable pathways towards circular economy [103].

3.3. Design of plastic MCPs

Poor plastic components and products design can have a huge impact on their recyclability. Plastics can only be recycled economically if recycling is built into their design. As evidence gathered in this study shows, recycling becomes very complex when dealing with the multiplicity of plastic components and products (e.g. multilayer plastics, flexible plastics, coloured plastics) that are already in widespread use in the market. The "design for recycling and from recycling" is the new concept-strategy put forward by the Ellen MacArthur foundation in their latest report on "rethinking the future of plastics" [65]. According to this new challenge the recyclability aspect should be incorporated as one of the top performance criteria, together with e.g. product safety, performance, marketing and branding, etc. A balance between all those objectives, prioritising the recyclability of a plastic product, should be achieved.

For designers, determining which guidelines should be put on top is a challenging task that depends largely on the way the product is recovered. Any advances in the technologies implemented in MRFs could potentially alter the MCP's end-of-life scenario; thus, what is considered a good design today may not be the case tomorrow [105]. Furthermore, designing with the intention to achieve an easy disassembly often comes in conflict with other critical product requirements. Companies may be reluctant design their MCPs in order to obtain recovery value if they consider that the economic benefits of this action are harvested by other stakeholders [66]. Nonetheless, it is the responsibility of brand owners to redesign their products in an easy-to-recycle way.

4. One for all and all for…plastics!

The collection, sorting, mechanical reprocessing and redistribution of PCPW back into the system appear to streamline the process of recycling PCPW, but low recycling rates suggest otherwise. Design, production, use, disposal, collection, sorting and reprocessing of PCPW inhibit the success of the recycling process and create a number of challenges in maximising the recovery of value from PCPW. This is partly attributed to a highly fragmented value chain and an underdeveloped market for recycled plastics, as well as the lack of traceability and transparency in the system [106]. Whereas virgin plastic suppliers are worldwide well-connected, recycled plastic suppliers, as well as reprocessors are often small, operating regionally or nationally [107]. Moreover, collection, sorting and reprocessing industries operating in the same system, are often controlled by different organisations with different interests adding further complexity to closing the plastic material loops.

Increasing the plastic waste recycling rates necessitates institutional, organisational and technological changes and a transparent communication and collaboration between all stakeholders (e.g., raw plastic material providers, plastic component and product manufacturers, retailers, consumers, waste managers, LAs, governments, regulators and non-governmental organizations) involved in the plastic value chain. Improved communication between all stakeholders can help align their interests, and incentivise manufacturers to change plastic components and products design. In turn this can increase PCPW recyclability and reduce externalities accumulated along the value chain [106]. A combined effort in improving the communication and coordination between all stakeholders and resolving the challenges related to closing the plastic materials loops, is urgently needed. This will ensure that the quality, quantity and procurement of recycled plastics remains consistent over time, supporting improvements in the supply and demand behaviour of the system. It is anticipated that as the plastics industry places more attention to increasing the plastic waste recycling, producers of virgin plastics, as well as waste collection companies will transform their own practices in order to rise to the occasion [107].

An inventory of design guidelines should be created, considering also any end-of-life scenarios (e.g. the guidelines for designing recyclates developed by Partners for Innovation) [108]. For designers, it is fundamental to comprehend which are the priority design guidelines. Industrial sector should improve and balance the supply and demand through e.g. online platforms. Local governmental entities can stimulate closed loop recycling of plastics, through various initiatives and campaigns, as well as through setting restrictions and fees on landfilling, and incineration, reducing at the same time taxes for recyclates use. Governments should also direct investments towards plastics recycling facilities and relative research & development (R&D) technologies.

5. Conclusions

Increasing the amount of plastic waste recycled is currently a priority area at the European agenda [21, 109-111], yet we are still far from its implementation. Wider systemic issues, which are often overlooked or looked in isolation, are hampering the PCPW recycling process. Gaining insights into the multiplicity of challenges associated with the mechanical recycling of plastic waste, we unearthed a number of trade-offs that should be measured against environmental, economic, social and technical values. This will facilitate a deeper understanding of the positive and negative value creation in scaling up the PCPW recycling, and contribute to an emergent but increasingly urgent need for scrutiny in the sustainability of closing the plastic waste loops, setting up a future research agenda.

6. References

[1] Ellen MacArthur Foundation, Towards the Circular Economy, Report vol. 1. , (2012).

[2] Ellen MacArthur Foundation, The Circular Model e Brief History and School of Thought. Available: http://www.ellenmacarthurfoundation.org/circulareconomy/circular-economy/the-circular-model-brief-history-and-schools-ofthought (accessed 10.10.13.). , (2013).

[3] Ellen MacArthur Foundation, Towards the Circular Economy. EMAF, 2013 (London, UK). (2013).

[4] Ellen MacArthur Foundation, Circular Economy: Overview and principles (January 2015), Available at: http://www.ellenmacarthurfoundation.org/circular-economy/overview/principles), (2015).

[5] Ellen MacArthur Foundation, Growth Within: A Circular Economy Vision for a Competitive Europe., (2015).

[6] J. Korhonen, C. Nuur, A. Feldmann, S.E. Birkie, Circular economy as an essentially contested concept, Journal of Cleaner Production, 175 (2018) 544-552.

[7] J. Kirchherr, D. Reike, M. Hekkert, Conceptualizing the circular economy: An analysis of 114 definitions, Resources, Conservation and Recycling, 127 (2017) 221-232.

[8] P. Ghisellini, C. Cialani, S. Ulgiati, A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems, Journal of Cleaner Production, 114 (2016).

[9] A.M. Breure, J.P.A. Lijzen, L. Maring, Soil and land management in a circular economy, Science of The Total Environment, 624 (2018) 1125-1130.

[10] G.I. Broman, K.-H. Robèrt, A framework for strategic sustainable development, Journal of Cleaner Production, 140 (2017) 17-31.

[11] E. Iacovidou, C.A. Velis, P. Purnell, O. Zwirner, A. Brown, J. Hahladakis, J. Millward-Hopkins, P.T. Williams, Metrics for optimising the multi-dimensional value of resources recovered from waste in a circular economy: A critical review, Journal of Cleaner Production, 166 (2017) 910-938.

[12] EC, Closing the loop – An EU action plan for the Circular Economy, in: Communication COM(2015) 614/2, http://ec.europa.eu/priorities/jobs-growth-investment/circular-economy/docs/communication-action-plan-for-circular-economy_en.pdf., European Commission, Brussels, 2015.

[13] European Commission, Packaging and Packaging Waste, in, European Commission, Brussels, 2018.

[14] European Commission, Directive of the European Parliament and of the Councail on the reduction of the impact of certain plastic products on the environment, in: 2018/0172, 2018.

[15] European Commission, A European Strategy for Plastics in a Circular economy, in, European Commission, Available at: http://ec.europa.eu/environment/circular-economy/pdf/plastics-strategy-brochure.pdf, 2018.

[16] J.N. Hahladakis, E. Iacovidou, Closing the loop on plastic packaging materials: What is quality and how does it affect their circularity?, Science of The Total Environment, 630 (2018) 1394-1400.

[17] E. Iacovidou, A.P. Velenturf, P. Purnell, Quality of resources: A typology for supporting transitions towards resource efficiency using the single-use plastic bottle as an example, Science of the Total Environment, 647 (2019) 441-448.

[18] CIWM, WasteAid UK, From the land to the sea - How better solid waste management can improve the lives of the world's poorest and halve the quantity of plastic entering the oceans, in, © CIWM and WasteAid UK, Available at: https://www.ciwm.co.uk/Custom/BSIDocumentSelector/Pages/DocumentViewer.aspx?id=vc5BRH8zGg0I5dc2rU7%252bx%252bbATxmTVi7RTfcAtUGwko9ndDl2Vi2EFreLW5BXUDMvNHgZk25dvHppFVhCKA%252fQVtSMtpaXNl49%252bGrGSe1gz9D1x%252fXa3FFB0RvAQOxRbiw%252f, 2018.

[19] R. Geyer, J.R. Jambeck, K.L. Law, Production, use, and fate of all plastics ever made, Science Advances, 3 (2017).

[20] L. Finska, Did the latest Resolution on Marine Plastic Litter and Microplastics take us any closer to pollution-free oceans?, in, The JCLOS Blog Available at: http://site.uit.no/jclos/files/2018/01/JCLOS-Blog-100118_Marine-Litter_Finska.pdf, 2018.

[21] European Commission, A European Strategy for Plastics in a Circular Economy. Available at: http://ec.europa.eu/environment/circular-economy/pdf/plastics-strategy.pdf, (2018).

[22] WRAP, The UK Plastics Pack, in, Waste and Resources Action Programme (WRAP), Available at: http://www.wrap.org.uk/content/the-uk-plastics-pact, 2018.

[23] E. Watkins, J.-P. Schweitzer, Moving towards a circular economy for plastics in the EU by 2030, in: Think 2030, Institute for European Environmental Policy (IEEP), Brussels, 2018.

[24] U. Arena, M.L. Mastellone, F. Perugini, Life Cycle assessment of a plastic packaging recycling system, The International Journal of Life Cycle Assessment, 8 (2003) 92.

[25] V. Wollny, G. Dehoust, U.R. Fritsche, P. Weinem, Comparison of Plastic Packaging Waste Management Options: Feedstock Recycling versus Energy Recovery in Germany, Journal of Industrial Ecology, 5 (2001) 49-63.

[26] T. Chilton, S. Burnley, S. Nesaratnam, A life cycle assessment of the closed-loop recycling and thermal recovery of post-consumer PET, Resources, Conservation and Recycling, 54 (2010) 1241-1249.

[27] A.L. Craighill, J.C. Powell, Lifecycle assessment and economic evaluation of recycling: A case study, Resources, Conservation and Recycling, 17 (1996) 75-96.

[28] S. Wenisch, P. Rousseaux, H. Métivier-Pignon, Analysis of technical and environmental parameters for waste-to-energy and recycling: household waste case study, International Journal of Thermal Sciences, 43 (2004) 519-529.

[29] M. Al-Maaded, N.K. Madi, R. Kahraman, A. Hodzic, N.G. Ozerkan, An Overview of Solid Waste Management and Plastic Recycling in Qatar, Journal of Polymers and the Environment, 20 (2012) 186-194.

[30] Å. Moberg, G. Finnveden, J. Johansson, P. Lind, Life cycle assessment of energy from solid waste—part 2: landfilling compared to other treatment methods, Journal of Cleaner Production, 13 (2005) 231-240.

[31] F. Perugini, M.L. Mastellone, U. Arena, Environmental Aspects of Mechanical Recycling of PE and PET: A Life Cycle Assessment Study, Progress in Rubber, Plastics and Recycling Technology, 20 (2004) 69-84.

[32] F. Perugini, M.L. Mastellone, U. Arena, A life cycle assessment of mechanical and feedstock recycling options for management of plastic packaging wastes, Environmental Progress, 24 (2005) 137-154.

[33] S. Rajendran, A. Hodzic, L. Scelsi, S. Hayes, C. Soutis, M. AlMa'adeed, R. Kahraman, Plastics recycling: insights into life cycle impact assessment methods, Plastics, Rubber and Composites, 42 (2013) 1-10.

[34] S.M. Al-Salem, S. Evangelisti, P. Lettieri, Life cycle assessment of alternative technologies for municipal solid waste and plastic solid waste management in the Greater London area, Chemical Engineering Journal, 244 (2014) 391-402.

[35] S. Ferreira, M. Cabral, N.F. da Cruz, P. Simões, R.C. Marques, Life cycle assessment of a packaging waste recycling system in Portugal, Waste Management, 34 (2014) 1725-1735.

[36] W.R. Lea, Plastic incineration versus recycling: a comparison of energy and landfill cost savings, Journal of Hazardous Materials, 47 (1996) 295-302.

[37] N.F. da Cruz, P. Simões, R.C. Marques, Economic cost recovery in the recycling of packaging waste: the case of Portugal, Journal of Cleaner Production, 37 (2012) 8-18.

[38] C.L. Simões, L.M.C. Pinto, C. Bernardo, Environmental and economic analysis of end of life management options for an HDPE product using a life cycle thinking approach, Waste Management & Research, 32 (2014) 414-422.

[39] G. Faraca, V. Martinez-Sanchez, T.F. Astrup, Environmental life cycle cost assessment: Recycling of hard plastic waste collected at Danish recycling centres, Resources, Conservation and Recycling, 143 (2019) 299-309.

[40] J. Groot, X. Bing, H. Bos-Brouwers, J. Bloemhof-Ruwaard, A comprehensive waste collection cost model applied to post-consumer plastic packaging waste, Resources, Conservation and Recycling, 85 (2014) 79-87.

[41] R.K. Foolmaun, T. Ramjeeawon, Comparative life cycle assessment and social life cycle assessment of used polyethylene terephthalate (PET) bottles in Mauritius, The International Journal of Life Cycle Assessment, 18 (2013) 155-171.

[42] M.T. Brouwer, E.U. Thoden van Velzen, A. Augustinus, H. Soethoudt, S. De Meester, K. Ragaert, Predictive model for the Dutch post-consumer plastic packaging recycling system and implications for the circular economy, Waste Management, 71 (2018) 62-85.

[43] D.A. Russell, Sustainable (food) packaging–an overview, Food additives & contaminants: Part A, 31 (2014) 396-401.

[44] R. Cossu, S. Masi, Re-thinking incentives and penalties: Economic aspects of waste management in Italy, Waste Management, 33 (2013) 2541-2547.

[45] L. Rigamonti, S. Ferreira, M. Grosso, R.C. Marques, Economic-financial analysis of the Italian packaging waste management system from a local authority's perspective, Journal of Cleaner Production, 87 (2015) 533-541.

[46] M. Alwaeli, The impact of product charges and EU directives on the level of packaging waste recycling in Poland, Resources, Conservation and Recycling, 54 (2010) 609-614.

[47] J.N. Hahladakis, P. Purnell, E. Iacovidou, C.A. Velis, M. Atseyinku, Post-consumer plastic packaging waste in England: Assessing the yield of multiple collection-recycling schemes, Waste Management, 75 (2018) 149-159.

[48] K. Ragaert, L. Delva, K. Van Geem, Mechanical and chemical recycling of solid plastic waste, Waste Management, 69 (2017) 24-58.

[49] J.M. García, Catalyst: Design Challenges for the Future of Plastics Recycling, Chem, 1 (2016) 813-815.

[50] M.E. Grigore, Methods of Recycling, Properties and Applications of Recycled Thermoplastic Polymers, Recycling, 2 (2017) 24.

[51] C. Meran, O. Ozturk, M. Yuksel, Examination of the possibility of recycling and utilizing recycled polyethylene and polypropylene, Materials & Design, 29 (2008) 701-705.

[52] P. Brachet, L.T. Høydal, E.L. Hinrichsen, F. Melum, Modification of mechanical properties of recycled polypropylene from post-consumer containers, Waste Management, 28 (2008) 2456-2464.

[53] H. Jin, J. Gonzalez-Gutierrez, P. Oblak, B. Zupančič, I. Emri, The effect of extensive mechanical recycling on the properties of low density polyethylene, Polymer Degradation and Stability, 97 (2012) 2262-2272.

[54] S. Yin, R. Tuladhar, F. Shi, R. Shanks, M. Combe, T. Collister, Mechanical reprocessing of polyolefin waste: A review, 2015.

[55] D. Achilias, E.V. Antonakou, C. Roupakias, P. Megalokonomos, A. Lappas, Recycling techniques of polyolefins from plastic wastes, 2008.

[56] S.M. Al-Salem, P. Lettieri, J. Baeyens, Recycling and recovery routes of plastic solid waste (PSW): A review, Waste Management, 29 (2009) 2625-2643.

[57] L. Delva, S. Hubo, L. Cardon, K. Ragaert, On the role of flame retardants in mechanical recycling of solid plastic waste, Waste Management, 82 (2018) 198-206.

[58] OECD, Improving Plastics Management, (2018).

[59] R. Geyer, J.R. Jambeck, K.L. Law, Production, use, and fate of all plastics ever made, Science Advances, 3 (2017) e1700782.

[60] Veolia, PLASTIC RECYCLING: a key link in the circular economy, in, VEOLIA, Published on 22 October 2018 - Updated on 18 April 2019, Available at: https://www.planet.veolia.com/en/plastic-recycling, 2018.

[61] W. d'Ambrières, Plastics recycling worldwide: current overview and desirable changes, Field Actions Science Reports [Online],, (2019).

[62] PlasticsEurope, Plastics – the Facts 2018. An analysis of European plastics production, demand and waste data. Available at: https://www.plasticseurope.org/application/files/6315/4510/9658/Plastics_the_facts_2018_AF_web.pdf, in, PlasticsEurope AISBL, Brussels, Belgium, 2018.

[63] A. Bartl, Circular Economy: Cycles, Loops and Cascades, ISWA Resource Management Task Force Report No.2, in, International Solid Waste Association (ISWA), Vienna, Austria, 2015.

[64] S. Kim, T. Hwang, K.M. Lee, Allocation for cascade recycling system, The International Journal of Life Cycle Assessment, 2 (1997) 217.

[65] Ellen MacArthur Foundation, The New Plastics Economy — Rethinking the future of plastics. Availbale at: https://www.ellenmacarthurfoundation.org/assets/downloads/EllenMacArthurFoundation_TheNewPlasticsEconomy_Pages.pdf, (2016).

[66] G. Coates, T. Staikos, C. Edwards, M. Abu-Bakar, Barriers, drivers and challenges for sustainable product recovery and recycling AU - Rahimifard, S, International Journal of Sustainable Engineering, 2 (2009) 80-90.

[67] J. Samsonek, J. Knoop, M. Egelkraut-Holtus, M. Ortlieb, Evidence of waste electrical and electronic equipment (WEEE) relevant substances in polymeric food-contact articles sold on the European market AU - Puype, Franky, Food Additives & Contaminants: Part A, 32 (2015) 410-426.

[68] S.-J. Chen, Y.-J. Ma, J. Wang, M. Tian, X.-J. Luo, D. Chen, B.-X. Mai, Measurement and human exposure assessment of brominated flame retardants in household products from South China, Journal of Hazardous Materials, 176 (2010) 979-984.

[69] H. Dahlbo, V. Poliakova, V. Mylläri, O. Sahimaa, R. Anderson, Recycling potential of post-consumer plastic packaging waste in Finland, Waste Management, 71 (2018) 52-61.

[70] C. Cole, M. Quddus, A. Wheatley, M. Osmani, K. Kay, The impact of Local Authorities' interventions on household waste collection: A case study approach using time series modelling, Waste Management, 34 (2014) 266-272.

[71] J. Carey, News Feature: On the brink of a recycling revolution?, Proceedings of the National Academy of Sciences, 114 (2017) 612-616.

[72] WRAP, Design tips for making rigid plastic packaging more recyclable, in: V1 18/10/2018, Waste and Resources Action Programme, Banbury, UK, 2018.

[73] RDC-Environment, Pira International, Evaluation of costs and benefits for the achievement of reuse and recycling targets for the different packaging materials in the frame of the packaging and packaging waste directive 94/62/EC" – Final consolidated report
in, RDC-Environment and Pira International, 2003.

[74] O. Horodytska, F.J. Valdés, A. Fullana, Plastic flexible films waste management – A state of art review, Waste Management, 77 (2018) 413-425.

[75] J.M. Soto, G. Blázquez, M. Calero, L. Quesada, V. Godoy, M.Á. Martín-Lara, A real case study of mechanical recycling as an alternative for managing of polyethylene plastic film presented in mixed municipal solid waste, Journal of Cleaner Production, 203 (2018) 777-787.

[76] E. Iacovidou, S. Gerassimidou, Sustainable Packaging and the Circular Economy: An EU Perspective, in: Reference Module in Food Science, Elsevier, 2018.

[77] D. Lazarevic, E. Aoustin, N. Buclet, N. Brandt, Plastic waste management in the context of a European recycling society: Comparing results and uncertainties in a life cycle perspective, Resources, Conservation and Recycling, 55 (2010) 246-259.

[78] T. Astrup, T. Fruergaard, T.H. Christensen, Recycling of plastic: accounting of greenhouse gases and global warming contributions, Waste Management & Research, 27 (2009) 763-772.

[79] L. Rigamonti, M. Grosso, J. Møller, V. Martinez Sanchez, S. Magnani, T.H. Christensen, Environmental evaluation of plastic waste management scenarios, Resources, Conservation and Recycling, 85 (2014) 42-53.

[80] European Environment Agency, The circular economy and the bioeconomy - Partners in sustainability, in, 2018.

[81] Geert Bergsma, Lonneke de Graaff, Sanne Nusselder, Ingrid Odegard, E.R. Lindgreen, Biobased Plastics in a Circular Economy. Policy suggestions for biobased and biobased biodegradable plastics, in, Delft, CE Delft, 2017.

[82] G.L. Robertson, Biobased but not biodegradable, Food Technology, 68 (2014) 61-70.

[83] F.R. Beltrán, C. Infante, M.U. de la Orden, J. Martínez Urreaga, Mechanical recycling of poly(lactic acid): Evaluation of a chain extender and a peroxide as additives for upgrading the recycled plastic, Journal of Cleaner Production, 219 (2019) 46-56.

[84] D. Maga, M. Hiebel, N. Thonemann, Life cycle assessment of recycling options for polylactic acid, Resources, Conservation and Recycling, 149 (2019) 86-96.

[85] M. Karamanlioglu, R. Preziosi, G.D. Robson, Abiotic and biotic environmental degradation of the bioplastic polymer poly(lactic acid): A review, Polymer Degradation and Stability, 137 (2017) 122-130.

[86] J. Hopewell, R. Dvorak, E. Kosior, Plastics recycling: challenges and opportunities, Philosophical transactions of the Royal Society of London. Series B, Biological sciences, 364 (2009) 2115-2126.

[87] F. Vilaplana, S. Karlsson, Quality Concepts for the Improved Use of Recycled Polymeric Materials: A Review, Macromolecular Materials and Engineering, 293 (2008) 274-297.

[88] N. Platzer, Polymer Degradation – Principles and Practical Applications, Wolfram Schnabel, MacMillan, New York, 1982, 227 pp. No price given, Journal of Polymer Science: Polymer Letters Edition, 20 (1982) 509-509.

[89] J.N. Hahladakis, C.A. Velis, R. Weber, E. Iacovidou, P. Purnell, An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling, Journal of Hazardous Materials, 344 (2018) 179-199.

[90] M. Grigore, Methods of recycling, properties and applications of recycled thermoplastic polymers, Recycling, 2 (2017) 24.

[91] M.K. Eriksen, K. Pivnenko, M.E. Olsson, T.F. Astrup, Contamination in plastic recycling: Influence of metals on the quality of reprocessed plastic, Waste Management, 79 (2018) 595-606.

[92] J. Drummond, Implementation of Post Consumer Recycled Plastic in Electronic Products. , in: SPE Annual Technical Conference, Houston, Texas, 2015.

[93] K. Pivnenko, M.K. Eriksen, J.A. Martín-Fernández, E. Eriksson, T.F. Astrup, Recycling of plastic waste: Presence of phthalates in plastics from households and industry, Waste Management, 54 (2016) 44-52.

[94] S.M. Al-Salem, P. Lettieri, J. Baeyens, The valorization of plastic solid waste (PSW) by primary to quaternary routes: From re-use to energy and chemicals, Progress in Energy and Combustion Science, 36 (2010) 103-129.

[95] J. Yu, L. Sun, C. Ma, Y. Qiao, H. Yao, Thermal degradation of PVC: A review, Waste Management, 48 (2016) 300-314.

[96] D. Ayre, Technology advancing polymers and polymer composites towards sustainability: A review, Current Opinion in Green and Sustainable Chemistry, 13 (2018) 108-112.

[97] E. Manias, L.A. Utracki, Thermodynamics of polymer blends, Polymer Blends Handbook, (2014) 171-289.

[98] L.A. Utracki, C.A. Wilkie, Polymer blends handbook, Springer, 2002.

[99] F. Nicolli, N. Johnstone, P. Söderholm, Resolving failures in recycling markets: the role of technological innovation, Environmental Economics and Policy Studies, 14 (2012) 261-288.

[100] C. Bach, X. Dauchy, M.-C. Chagnon, S. Etienne, Chemical compounds and toxicological assessments of drinking water stored in polyethylene terephthalate (PET) bottles: A source of controversy reviewed, Water Research, 46 (2012) 571-583.

[101] M. Whitt, W. Brown, J.E. Danes, K.L. Vorst, Migration of heavy metals from recycled polyethylene terephthalate during storage and microwave heating, Journal of Plastic Film & Sheeting, 32 (2016) 189-207.

[102] A. Genovese, A.A. Acquaye, A. Figueroa, S.C.L. Koh, Sustainable supply chain management and the transition towards a circular economy: Evidence and some applications, Omega, (2015).

[103] E. Iacovidou, J. Millward-Hopkins, J. Busch, P. Purnell, C.A. Velis, J.N. Hahladakis, O. Zwirner, A. Brown, A pathway to circular economy: Developing a conceptual framework for complex value assessment of resources recovered from waste, Journal of Cleaner Production, 168 (2017) 1279-1288.

[104] E. Iacovidou, C.A. Velis, P. Purnell, O. Zwirner, A. Brown, J. Hahladakis, J. Millward-Hopkins, P.T. Williams, Metrics for optimising the multi-dimensional value

of resources recovered from waste in a circular economy: A critical review, Journal of Cleaner Production, 166 (2017) 910-938.

[105] E. Masanet, R. Auer, D. Tsuda, T. Barillot, A. Baynes, An assessment and prioritization of" design for recycling" guidelines for plastic components. In Electronics and the Environment, 2002 IEEE International Symposium on IEEE. , in, 2002, pp. 5-10.

[106] L. Milios, L. Holm Christensen, D. McKinnon, C. Christensen, M.K. Rasch, M. Hallstrøm Eriksen, Plastic recycling in the Nordics: A value chain market analysis, Waste Management, 76 (2018) 180-189.

[107] D. Froelich, E. Maris, N. Haoues, L. Chemineau, H. Renard, F. Abraham, R. Lassartesses, State of the art of plastic sorting and recycling: Feedback to vehicle design, Minerals Engineering, 20 (2007) 902-912.

[108] I. Gort, A. Gerrits, Ontwerpen met Kunststof Recyclaat. Retrieved from http://www.partnersforinnovation.com/media/Guidelines-Ontwerpen-met-Recyclaatfinal.pdf, in, 2015.

[109] European Commission, Closing the Loop - An EU Action Plan for the Circular Economy. Communication From the Commission to the European Parliament. The Council, the European Economic and Social Committee and the Committee of the Regions., (2015).

[110] European Commission, Closing the loop. New circular economy package. Available at: http://www.europarl.europa.eu/RegData/etudes/BRIE/2016/573899/EPRS_BRI(2016)573899_EN.pdf, (2016).

[111] European Commission, Towards a circular economy: a zero waste programme for Europe. Communication From the Commission to the European Parliament. The

Council, the European Economic and Social Committee and the Committee of the Regions, Brussels (EN). (2014).

List of Figures

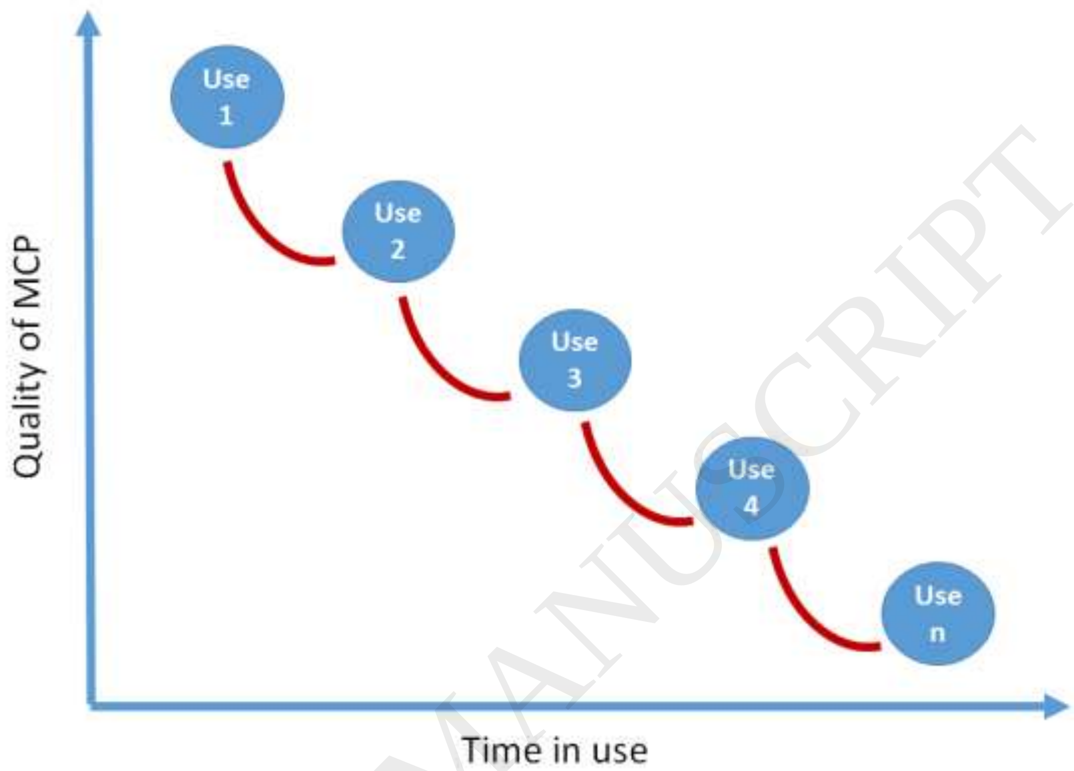

Fig. 1.

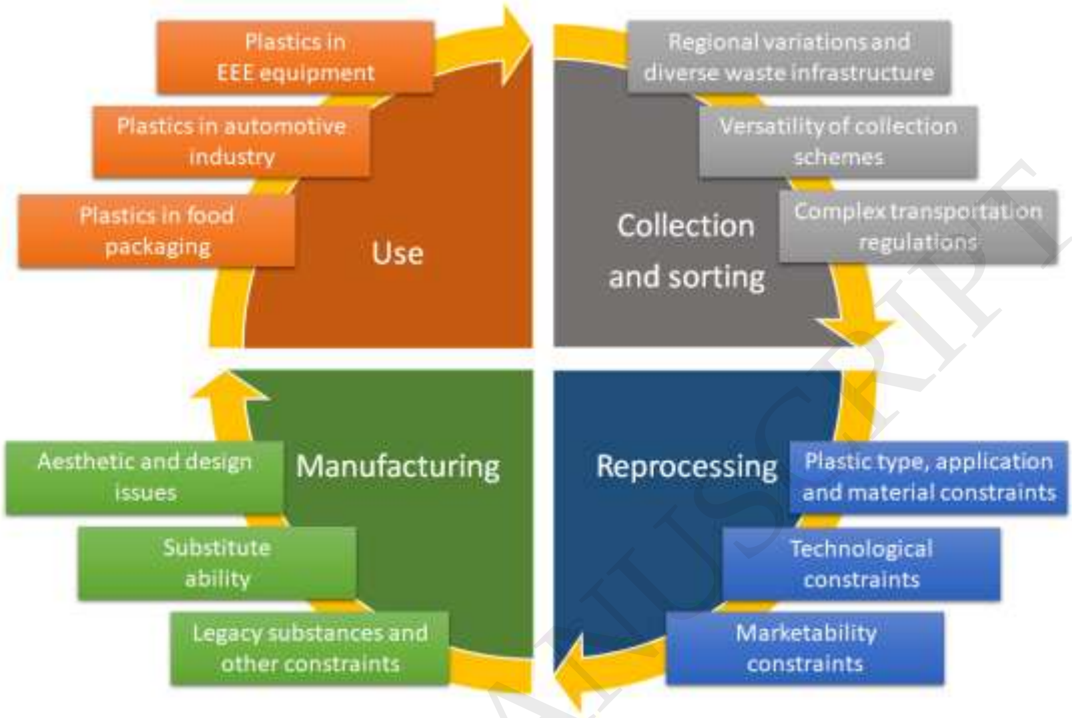
Plastics in
EEE equipment
Plastics in automotive
industry
Plastics in food
packaging
Use
Regional variations and
diverse waste infrastructure
Versatility of collection
schemes
Complex transportation
regulations
Collection
and sorting
Aesthetic and design
issues
Substitute
ability
Legacy substances and
other constraints
Manufacturing
Reprocessing
Plastic type, application
and material constraints
Technological
constraints
Marketability
constraints

Fig. 2.

Tables

Table 1

Challenges and trade-offs of plastic waste mechanical recycling

Table 1

Challenge	Description	Trade-off(s)
Composition	*Petrochemical-based:* the incompatibility between the different types of polymers, in regards to structure, melting points and processing temperature, can cause changes in the recycled polymers structure when one polymers ends up in another polymer's stream, and may release substances that may cause damage (e.g. corrosion) to the reprocessing equipment [69, 72, 92, 94-96].	▪ Promotes rejection of recycled plastic due to deterioration of material properties (e.g. PVC in PET or PP) - leads to negative value creation ▪ Negative externalities due to equipment corrosion ▪ Generates unwillingness in reprocessors to take in waste that is not well-sorted ▪ Increases the potential of polymer blending (e.g. PP in PE streams) that has reduced mechanical properties [97, 98] - leads to cascade recycling
	Bio-based: the increasing variety in bio-based plastics that are often misplaced in the mixed PCPW stream cannot be effectively separated from the petrochemical-based plastics, can compromise the recyclability of the petrochemical-based plastic waste stream, and causes problems in the equipment [16].	▪ Promotes rejection of recycled plastic due to deterioration of material properties - leads to negative value creation ▪ Negative externalities due to equipment corrosion
Sorting ability	*Material focused:* currently only rigid, high value, mono-polymer type of plastics (e.g. PET, PE, PP) are sorted for reprocessing [48, 69].	▪ Excludes the recycling of plastics that are of low bulk density (i.e. films and carrier bags), light-weight (e.g. PS) or have a low market value (e.g. PS) [71] – leads to negative value creation ▪ Creates a lock-in effect to already pre-established recycling systems
	Colour focused: carbon black pigments absorb the infra-red light and cannot be sorted [71, 72]. Not all coloured plastics are sorted.	▪ Increases the rejection of black and other coloured plastics – leads to negative value creation ▪ Hinders the level of recycled content in coloured plastics (they can only be turned black) - leads to negative externalities and negative value creation [72]
	Technology focused: the use of near infrared (NIR) technology and accompanied techniques for plastic sorting are not sufficient to ensure that contamination is circumvented [90].	▪ Reduces the amount of plastics sorted for recycling – leads to negative value creation ▪ Introduces contamination in the plastic streams – leads to negative externalities ▪ Promotes advances in technologies ability to recognize waste that centralise the recycling process and overcome market failures [99] - leads to both positive and negative value creation ▪ Fosters local growth by reintroducing manual sorting and promoting employment - leads to positive value creation
Contamination	*Designed contaminants:* they can spread, accumulate and affect the mechanical (e.g. tensile strength, impact) and rheological properties of the polymers, affecting their recyclability potential [16, 71]. They may remain in the plastic even after the reprocessing stage [89, 100, 101].	▪ Prevents closed-loop recycling – leads to cascade recycling ▪ Promotes rejection of recycled plastic due to deterioration of material properties [72] – leads to negative value creation ▪ Restricts the use of recycled plastic content in new products – leads to negative externalities

		▪ Negative externalities due to equipment corrosion ▪ Increases the risk of concentration of substances in recycled materials ('legacy substances') [23, 71] - leads to negative value creation
	Created contaminants (i.e. impurities): they can create small imperfections on the plastic's surface, leading to an uneven surface, creating splays and poor scratch resistance, which can impact the final appearance of the recycled material, [91, 102]	▪ Promotes rejection of recycled plastic due to deterioration of material properties - leads to negative value creation ▪ Increases the potential of creating blends (e.g. PP in PE stream) that have reduced mechanical properties, and lower the quality of the polymer [97, 98] - leads to cascade recycling
Degradation at reprocessing	Plastic waste materials undergo mechanical (i.e. shear forces effects) and thermal (i.e. high temperature effect) degradation that change their molecular weight, molecular weight distribution, crystallinity and chain flexibility of the polymer [17, 56, 87-89].	▪ Results in instability of material properties [17, 48, 89, 92] – leads to cascade recycling ▪ Leads to shorter overall life each cycle [17, 48, 89, 92]
Degradation at service life	Aggravates degradation at mechanical reprocessing; the presence of oxygen in the air leads to the formation of low-molecular compounds that are released during the reprocessing and may diffuse through the melt and compromise the processing efficiency, corrode the processing equipment and induce structural changes in the final properties of the material [48, 69]	▪ Yields a low quality material – leads to cascade recycling ▪ Promotes rejection of recycled plastic due to deterioration of material properties – creating negative externalities and value creation
Compatibilization	Enables the blending of polymers (two or more) that are often incompatible by the use of a compatibilizing agent in order to enable interfacial adhesion between immiscible polymers, and obtain the desired performance against the effect of thermal-mechanical degradation during reprocessing [17, 48].	▪ Permits only one cycle of plastic materials in the economy [17, 56] – leads to negative value creation ▪ Creates uncertainty in the quality of end-material which restricts its potential use – leads to negative externalities and negative value creation
Substituteability (in new component/ product)	Involves the use of an amount of recycled plastic materials to be blended with virgin polymer in the production of new products at varying concentration; generally less than 50% [96].	▪ Results in instability of the blend which may affect the durability of the material over its use [96] - leads to fast degradation and wastage ▪ Increases the risk of circulating potentially hazardous impurities above regulatory limits - leads to negative value creation
Marketability	Price fluctuations between virgin and recycled materials, and supply-demand dynamics for different types of plastics (e.g. PET, HDPE, PP, PS), as well as other market forces governed by regulations (e.g. EPR), infrastructure availability and asymmetric information [99, 102].	▪ Affects the demand of recyclable plastics [99] – leads to negative externalities ▪ Increases the risk of reprocessors not generating revenue (from selling the materials) – leads to negative externalities ▪ Suppresses the maximization of plastics recycling by expanding to other types – leads to negative value creation
Feasibility	Efficiency of the recycling process from an economic and environmental point of view. Involves the availability and overall costs of techniques and processes implemented to obtain the final product (separation, purification, etc.); ecological aspects (generation of dust, noise pollution by grinding, energy consumption, toxicity of applied solvents).	▪ Pauses investment and scaling up of the reprocessing facilities. ▪ Requires additional resources to reprocess the material due to the designed complexity – leads to negative value creation ▪ Enables the development of local recycling systems to emerge - leads to positive value creation