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Mapping the plastics system and its sustainability challenges

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Extended summary

Plastics are versatile materials with environmental, technical, economical and societal benefits, however plastics also contribute negatively to the environment and climate. Put in numbers around 4% of the fossil oil and gas is used as feedstock for plastics while another 4% is used for providing energy for the manufacturing of plastics. Many initiatives on reducing the negative effects of plastics are focusing on waste management, product design and consumer behaviour, however the fact that plastics originate from crude oil is sometimes neglected.

The plastics system faces major sustainability challenges. The utilization of fossil feedstock and energy in the production causes emissions of carbon dioxide. Insufficient waste management and recycling result in littering and resource inefficiency. Plastics are likely to continue to be an important material in a fossil free future, however for that a sustainability transition needs to take place. The question is how?

The report describes the current value chains including production, utilization and waste management of plastics as well as the sustainability challenges related to them. This extended summary highlights the most important sustainability challenges and gives some concrete examples of the difficulties and contradictions in achieving a more sustainable plastics system. The report is part of the Mistra funded research programme STEPS – Sustainable Plastics and Transition Pathways. The vision of the programme is to "…facilitate and accelerate transition of the plastic sector to a future society with sustainable production, use and recycling in a circular plastics economy." Based on that vision, the following questions are asked: What are sustainable plastics? What is the role of plastics in a sustainable society? And what are the key challenges?

Basic facts about plastics

Today, the global plastics production accounts for 4-8 % of the fossil oil consumption and over 335 Mton of plastics are produced annually. Below 1 % of the global production of plastics is produced from renewable feedstock. Statistics from the EU and Sweden show that big parts of plastics are used in long-lasting applications such as construction (20 %), automobile (9 %) and electronics (6 %). However, the biggest utilization category is packaging (40 %) (Plastics Europe, 2017).

There are two different types of plastics; thermosets and thermoplastics. Thermosets are hardened and cannot be softened or reshaped by heat. Thermoplastics on the other hand are softened when heated and can therefore be recycled into new plastic products through melting, re-granulation and formulation. There are about 700 different kinds of thermoplastics grouped into 18 polymer families. The most common are polyethylene (PE) and polypropylene (PP) (Plastics Europe, 2017).

Sustainable plastics

Sustainable plastics does not have a clear definition, but the starting point in the STEPS programme is the following: "A transition to a more sustainable plastics system involves an increase in the resource and material efficiency of plastics consumption, a significant increase in the reuse and recycling of plastics, a shift to new plastic additives with low environmental and health impacts, and a switch to renewable feedstock". This starting point is illustrated by Figure 1 and the extended summery highlight four main sustainability aspects; (i) renewable feedstock, (ii) resource efficiency (iii) waste management and recyclability and (iv) plastics leakage.

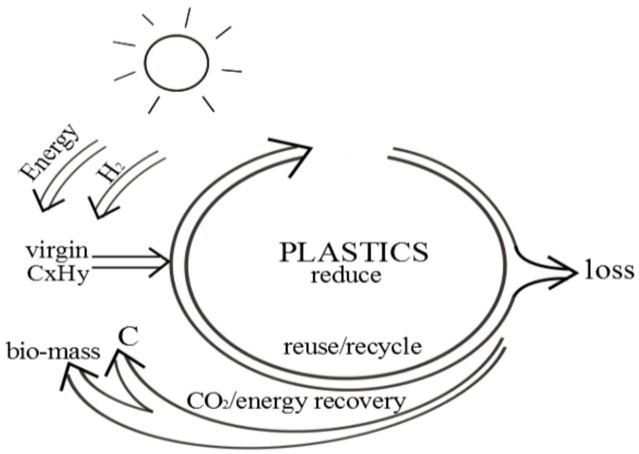

Figure 1: Conceptual drawing of a sustainable plastics system, illustrating the renewable feedstock, efficient utilization and waste management

Renewable feedstock

One of the key challenges regarding sustainability for plastics is that the plastics industry is currently highly dependent on fossil feedstock and energy. This eventually needs to change, and a future fossil-free economy require alternative feedstock that is both renewable and sustainable. Biomass is a good and viable option, but potential resource scarcity if all plastics, fuels and energy are to be bio-based makes it important to consider feedstock diversification. An integration of agro-industrial and forestry side streams, food wastes, carbon dioxide, methane and recycled plastics is important to cover the future plastics demand.

Resource efficiency

A sustainable plastics system could entail both an increased and decreased utilization of plastics. On the one hand, increased plastics use could lead to an increase in sustainability due to the environmental benefit of for example; food packaging, lightweight transportation, and material substitution. On the other hand, decreased use of plastics consumes less resources, which is also important irrespective of whether the feedstock is renewable or not. Regardless of this possible contradiction, it is certain that resource efficiency will be an important aspect in a future sustainable plastics system. An efficient use and recycling of plastics could involve using more plastics, without consuming more virgin feedstock.

Waste management and recyclability

An increased use of recycled material as plastic feedstock would decrease the demand for virgin resources and is likely to be an important aspect of a sustainable plastics system. This route is currently insufficiently implemented, and both 'design for recycling' of products and development of the waste management system is needed. High collection rates must be combined with high recycling rates. However, recycling is currently not an economically competitive option. In a fossil-free future, renewable feedstock is likely to be more expensive, and plastics therefore more attractive to recycle from an economic perspective. No system can be completely circular and there will always be downgrading and losses and therefore a need for virgin (renewable) feedstock. Nevertheless, increased recycling, and recyclability of materials and products, would lead to a decreased need of virgin feedstock.

Plastics leakage

The increased use of (mainly single-use) plastics has resulted in an increased amount of littering, both on land and to the oceans. Furthermore, there is diffuse leakage of plastics from car tires, clothes, etc. Since plastics are fairly stable, all plastic waste that is not collected within a waste management system, remains in nature essentially without degrading. Plastics in the natural environment is a sustainability concern of yet unknown proportions and effects. Therefore, handling the plastic littering issue is also an essential part in achieving a sustainable plastics system.

Examples illustrating the complexity of the challenge

The sustainability challenges related to plastics are illustrated via some examples of difficulties and contradictions that might occur when addressing a sustainability transition of the plastics system:

- Environmental policy can play a key role in achieving a sustainability transition, but the question is what and how to govern the transition. The Swedish government has decided on a national ban on microplastics in cosmetics that are washed off. At the same time, it has been shown that the microplastics from cosmetics represent a negligible share of the total microplastics pollution. The main sources are instead identified as littering, tires and artificial grass playing fields. Is a ban of microplastics in cosmetics an example of effective governing? See Section 4.2.
- There are several obstacles to increasing the use of recycled material in society. The largest plastics waste stream originates form household and this waste flow contains valuable plastics that are simple to recycle. However, the recyclable plastics waste from households is mixed in the collection with other less recyclable plastics, such as multi-layer films. As a result, only parts of the collected plastics become new recycled feedstock due to losses in the plastics sorting and in the preparation for recycling. See Chapter 5.
- Since a major issue with plastics is that they are durable, then perhaps biodegradable plastics could be the solution to land and ocean littering? It is suggested that in applications where utilization almost certainly involves leakage to the environment (such as mulch films), fully degradable plastics could be a more sustainable solution. However, biodegradable plastics also have drawbacks and challenges. The biodegradables of today demand special conditions to degrade, therefore they risk not being degraded if they end up in nature. Biodegradable plastics are also considered by the recycling industry to affect product quality if they are mixed into the stream of plastics aimed for recycling. See Section 3.5.2.
- From a business perspective, it is perceived to be problematic to market fossil-based and fossil-free product at the same time. This may slow down the transition and implementation of renewable feedstock. The difficulty of developing marketing strategies for a portfolio with both renewables and fossil-based products is one obstacle that applies to all industries with ambitions of a sustainability transition. Another obstacle might be that the public debate often focuses on littering issues, rather than on the fossil content of plastics. This may draw attention from the unsustainability of using fossil feedstock. See Section 4.4.
- Increased resource efficiency can be achieved in many ways. A common method to decrease the use of plastics feedstock is to add fillers to the polymers. However, the addition of fillers also changes the density and recyclability of the plastics. The complexity regarding sustainability then lies in either using fillers and thereby reducing use of polymers or instead using mono-materials that are more suitable for recycling. See Section 5.4.

Achieving sustainable plastics

There are numerous challenges in order to achieve a sustainable plastics system, and despite the complexity of the issue there are some promising changes taking place. For example, the European Commission recently published a Strategy for Plastics in a Circular Economy that addresses the need to increase recycling and decrease littering (European Commission, 2018). The plastics system involves a great number of actors with different roles in the sustainability transition. Who will initiate the change? Will it start with governing initiatives in form of new policy and legislation? Will the change origin from small start-ups that are ahead in terms of meeting customer demands for more sustainable products? Or will it be the global manufacturers and retailers that respond to the sustainability needs? Consumer demand alone will probably not be enough to achieve a transition towards more sustainable plastics. How can the transition to a future society with sustainable production, use and recycling in a circular plastics economy, be facilitated and accelerated? What governance approaches and policy instruments would be most effective?

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1 Introduction

1.1 Aim and scope

This report is part of the Mistra funded research programme STEPS – Sustainable Plastics and Transitions Pathways. It represents one of the first steps towards the programmes vision to:

> "Facilitate and accelerate transition of the plastics sector to a future society with sustainable production, use and recycling in a circular plastics economy."

The aim is to create an overview and understanding of the complex plastics system and to identify key sustainability challenges. The report consists of a mapping of the plastics production, consumption and waste management system. It focuses mainly on the Swedish context, with some comparisons to the EU context. Additives are not within the scope of the project; therefore, this report does not address sustainability issues connected to additives, except for additives that can negatively affect the recycling.

1.2 Method

The report relies on a broad range of literature, including scientific articles and reports, statistical sources and trade organisations. Furthermore, it has been carried out in dialogue with the STEPS industrial partners via an open-space format workshop based on a draft of the extended summary.

1.3 Outline of the report

The report starts with a general overview of what plastics are, including the production, consumption and waste management. The overview is an introduction for understanding the structure, numbers and logic of the plastics sector in general. In the upcoming chapters plastics production is further developed, describing the process from oil to plastics, different production technologies and plastics products. Both fossil and non-fossil routes are explained, and some Swedish examples are presented. The following chapters move one step further in the product chain, focusing on consumption of plastics and present the volume of various plastics streams in the EU and Sweden. Last, plastic waste management for different plastic fractions in the EU and in Sweden is described. The report ends with a discussion on the possible solutions, points of conflict and challenges in finding transition pathways to a sustainable plastics system.

2 Introduction to plastics

Plastics are all around us, and nowadays there is almost no one that does not come in contact with this ubiquitous material. But what are plastics? In this chapter, an introduction to plastics is given, including the history of its development, some key figures on production, consumption and recycling and a presentation of existing visions and initiatives to move towards a more sustainable plastics system.

Plastics were invented in the 19th century. The first man-made plastics was a cellulose nitrate-based plastic named Parkesine. It was patented by Alexander Parkes in 1856 (UK Patent Office, 1857). The early plastic production was bio-based and for example billiard balls were produced of the bioplastic celluloid in 1869 (ACG, 1993) and in the 1920s Ford cars had bioplastics in their interior (Timetoast, 2017). However, bioplastics were later outcompeted by its fossil counterpart. The key breakthrough came in 1907 when Leo Baekeland created Bakelite, the first real synthetic, mass-produced plastics (ACG, 1993), and the big scale industrial production begun after the second world war.

Plastics are a synthetic or semisynthetic material with a backbone consisting mainly of hydrogen and carbon. Today plastics are produced from fossil resources such as oil, coal and natural gas, but can in principle be produced from any source of hydrogen and carbon. Typically, they are polymers with a high molecular weight (SMED, 2012).

2.1 Plastics production

Plastics are produced by refining and cracking crude oil to monomer building blocks followed by polymerization to form polymers and finally manufacturing of plastics products. During the past 50 years, the annual global production of plastics has increased from 1.5 Mton to over 335 Mton (Plastics Europe, 2017). Despite the initial plastics being bio-based, the development has been almost exclusively fossil-based, due to both favourable price and the availability of fossil feedstock. The global plastics production is expected to continue to increase and the growth is driven mainly by increasing demand in developing economies (UNEP, 2012). Europe is the second largest producer of plastics, with an annual production of approximately 60 Mton (Plastics Europe, 2017). This translates into 200 Mton carbon dioxide turnover directly connected to the plastics sector (Lechtenböhmer et al., 2016).

The plastics industry has acknowledged that the fossil feedstock and energy use is a sustainability issue in relation to climate change and ambitions to decarbonise industry (e.g. Hållbar Kemi, 2016). Since bio-based plastics can reduce carbon dioxide emissions, it has gained an increased interest from both private and public actors. However, sustainably harvested biomass is a limited resource, that can become scarce due the competition of land use with for example, food and fuel (Tsiropoulos et al., 2014; Lechtenböhmer et al., 2016; Niewöhner et al., 2016; European Commission, 2012; Brodin et al., 2017).

2.2 Plastics consumption

Plastics are used in every sector of society and are often categorised according to: agriculture, electronics, automobile, building and construction, packaging and others. Packaging is by far the largest category of use and corresponds to almost 40 % of European plastics. In Section 4.1 the categories of use together with the type of plastics in various application are more extensively described.

The global consumption of virgin plastics is expected to grow in the future. If a global population of 8 to 9 billion people would consume plastics at the current Swedish level of 100 kg/capita and year, about 1 000 Mton/year of plastics would be needed (Palm et al., 2016). This can be compared to the current yearly demand of 335 Mton plastics.

The amount of plastics being consumed influences the sustainability of the plastics system. However, it is not obvious that reduced consumption would lead to a more sustainable system. Plastics contribute to energy efficiency by light weight transportation, insulation of buildings and decrease food waste via packaging. This implies that plastics consumption should not be set to a minimum but should instead be used in a more efficient way.

2.3 Plastics waste management

The fossil feedstock and unsustainable consumption are not the only obstacles to reach sustainability regarding plastics. The plastics system also needs improvement regarding resource efficiency and waste management by for example improved collection and increased recycling and re-use. Globally it is estimated that out of the 6300 Mton plastic waste produced, only around 9 % has been recycled and 12 % incinerated. Remaining 79 % of all plastic waste has been accumulated in either nature or landfills (Geyer et al., 2017). To tackle this issue the European Commission has established goals to increase recycling of plastics packaging, with the aim to reduce emissions and create a more efficient use of resources. Increasing the use of recycled plastics can lead to less plastics being produced by virgin material, which saves energy and resources. Thus, increased recycling is important irrespective of whether the feedstock is fossil or renewable (European Commission, 2017a).

Regarding resource efficiency, the recycling of plastics in the EU has increased over the last decade, and goals are set to increase it even further (Plastics Europe, 2017). In the European Commission's proposal for amending directive 94/62/EC on packaging and packaging waste with new targets, the proposed target for plastics material in packaging is that 60 % should be re-used and recycled by 2025 (European Commission, 2014a). At present, one third of all plastic waste in the EU goes to landfill and the Circular Economy Action Package proposes that no more than 10 % plastic waste should end up in landfill by 2030 (European Commission, 2017a). The Swedish legislation for recycling also concerns packaging and states that 50 % of the plastics packaging should be recycled after January 2020 (SFS 2014:1073). The same legislations also set targets for polymeric packaging of beverages (PET) to have a recycling rate of 90 %.

Two challenges regarding recycling are market demand and quality issues in the recycled material. It is considered essential to avoid contamination in the recycled streams in order to ensure quality, and thereby facilitate the economics of plastics recycling (European Commission, 2018a). In Sweden, with a reported recycling rate of around 50 %, it is estimated that only 13 % of the initial economic value of the plastic material is recovered via recycling and energy recovery (Material Economics, 2018). There is also a need for regulatory frameworks on biodegradable plastics since these plastics are considered by the recycling industry to affect quality if being mixed into the stream of recycling of durable plastics (European Commission, 2018a; Dagens Samhälle, 2016).

2.4 Visions and initiatives

Initiatives and visions towards a more sustainable plastics system are formulated both by policymakers and industry. The work conducted by the Ellen MacArthur foundation on a "New plastics economy" has been influential and can be seen in many policy and industrial initiatives (Neufeld et al. 2016; MacArthur et al., 2017). Plastics are defined as one of five priority sectors in the EU ´Circular Economy´ package. The starting point in this work has been the green paper on a European Strategy on Plastic Waste in the Environment (European Commission, 2013). The aim is to tackle the need for a strategic approach for plastics production and plastic waste management. The green paper targets two challenges that need to be addressed regarding plastics and sustainability. The first challenge is plastics debris in the seas and for example the impact of chemical additives. The second is resource conservation, including recycling and circular economy. The most recent publication from the action plan connected to the ´Circular Economy´ package is the Plastics Strategy. In January 2018 the European Commission published a "Strategy for Plastics in the Circular Economy" highlighting two key areas: increased recycling and decreased littering (European Commission, 2018a). Prior to that a "Roadmap for the strategy on plastics in the circular economy" was published highlighting three issues: high dependence on virgin fossil feedstock, low rate of recycling and reuse of plastics, and significant leakage of plastics into the environment (European Commission, 2017b). There has thus been a shift in priority regarding the dependence on fossil feedstock since it is no longer stated as a key priority. However, driving innovation towards circular economy and renewable feedstock are mentioned and recycled plastics can be considered a way of moving away from (virgin) fossil feedstock.

Beside the recently released Plastic Strategy there appears to be a global policy trend to address sustainability challenges mainly on the consumption side of the plastics system, such as policy for a reduced use or bans on plastic bags (Xanthos and Walker, 2017; Tillväxtanalys, 2018). The aim is often twofold, to both reduce littering and to create an awareness on unnecessary and unsustainable consumption. In some cases, it is also aimed to be a measure for achieving a better utilization of resources, a way to decrease the use of fossil resources (Convery et al., 2007; Poortinga et al., 2013).

However, in line with the EU Strategy for Plastics in a Circular Economy, the Swedish government has recently initiated work on an official report of the Swedish government on plastics and sustainability. This initiative aims to tackle the plastic challenges more broadly and the report is to be ready by the end of 2018 (Regeringen, 2017). In short, the report will identify the environmental consequences of the plastics system, including production, utilisation, recycling and plastic leakage and also suggest cost effective ways to reduce these negative environmental effects.

The Swedish legislative deposit system for bottles and cans has been expanded. The legislation forces PET bottles for beverages, excluding juices and syrups, into the deposit system. But, since September 2015 manufacturers of lemonade can voluntarily register into the system. Axfood was the first to connect their lemonade products, and the number of brands included is growing (Returpack, 2017). Two examples of incentives from the industry that target the production rather than the recycling are the bio-based polyethylene plastics in some milk containers (Arla, 2017) and PET bottles with 25 % content of bio-based material (Coca Cola Company, 2017).

3 Plastics production

Current plastics production is derived from oil, coal and natural gas, but plastics can in principle be produced from any source of hydrogen and carbon. In this chapter, the production is described from oil to plastics including different production technologies and plastics manufacturing. Non-conventional routes are also described, such as bio-based plastics, electricity and carbon dioxide-based plastics and plastics that are biodegradable to some degree.

The global plastics production of 335 Mton accounts for 4-8 % of fossil oil, approximately half is used as feedstock and half for energy purposes (Thompson et al., 2009). Global plastics production has increased dramatically during the past 10 years, and projections show a continued increase (Plastics Europe, 2017). The growth is expected to take place mainly Asia, Africa and South America, while the European production is expected to remain stable (UNEP, 2012; Cefic, 2013).

3.1 Refining and cracking

The process of producing plastics starts with refining. The hydrocarbon molecules in the crude oil are sorted by molecular size, i.e. boiling point. The lightest fraction with the lowest boiling point contains short hydrocarbons like naphtha, propane and butane. These lighter hydrocarbons are cracked to smaller building blocks such as ethylene and propylene by high temperature. These smaller building blocks are later used in the polymerization facilities (SPBI, 2017).

In Sweden, there are five crude oil refineries, all located in the southern part of the country. Three are in Gothenburg (operated by Preem, st1, Nynas), one in Lysekil (operated by Preem) and the last one is in Nynäshamn (operated by Nynas). Preem in Lysekil and st1 in Gothenburg provide feedstock to the petrochemical plastics industry. The two refineries operated by Nynas focus the production on special oils for construction of roads, lubrication and plasticiser for rubbers and lastly Preemraff in Gothenburg produces among other things, diesel (Preem, 2017). In Sweden there are two crackers, but only Borealis Group in Stenungsund crack light hydrocarbons to plastics monomers (Svahn, 2017).

3.2 Polymerization

The polymerization is the production of long molecular chains from monomers. This can be done in two ways, either by poly-condensation or poly-addition. Poly-condensation requires at least two reactive groups on the monomer unlike poly-addition which instead requires a double bond. The two most common plastics, polyethylene (PE) and polypropylene (PP) are formed via poly-addition from ethylene and propylene respectively. In this process, the double-bonds in the monomer are broken in the formation of the polymer. In contrast, the production of polyethylene terephthalate (PET) takes place via poly-condensation in two steps. The monomers dimethyl terephthalate and ethylene glycol form ethylene terephthalate which are then polymerized to PET (SLI, 2017).

In Sweden there are two plastics producers, Borealis and Inovyn. Borealis produces a wide range of plastics, such as granulates for production of packages, both hard plastics and plastics films and PP-fibres. For technical applications, Borealis also produces high quality polyethylene for underwater high voltage cables (Borealis, 2017). Inovyn is Europe's largest producer of PVC. Inovyn also recycle PVC (Inovyn, 2017). In Europe, there are other big plastics producers and manufacturers of plastic products, for example: ExxonMobil Chemicals, BASF, Bayer, and DuPont.

3.3 The variety of plastics

Plastics are divided into two different types; thermosets and thermoplastics. Thermosets are hardened and cannot be softened or reshaped by heat. Almost all consumer plastics are thermoplastics, plastics that soften when heated and therefore can be reshaped. There are about 700 different kinds of thermoplastics grouped into 18 polymer families. The most common polymer families are polyethylene (PE) and polypropylene (PP), and they are used in a wide range of products; packaging, cutlery, furniture etc. Polyvinylchloride (PVC), in which chlorine is added to the ethylene, are typically used in pipes, industrial applications and in construction. Polyethylene terephthalate (PET) is common in packaging and as a fibre for the textile industry. Finally, Polyurethane (PUR) is often expanded to foams for example to mattresses and Polystyrene (PS) can be used as expanded polystyrene that protects electronics (SMED, 2012). Figure 2 shows the percentage usage of these polymer families in Europe. The group 'Others', representing for example Polytetrafluoroethylene (PTFE) in Teflon coatings, are also a large portion of the plastics produced indicating the complexity and diversity of the plastics system.

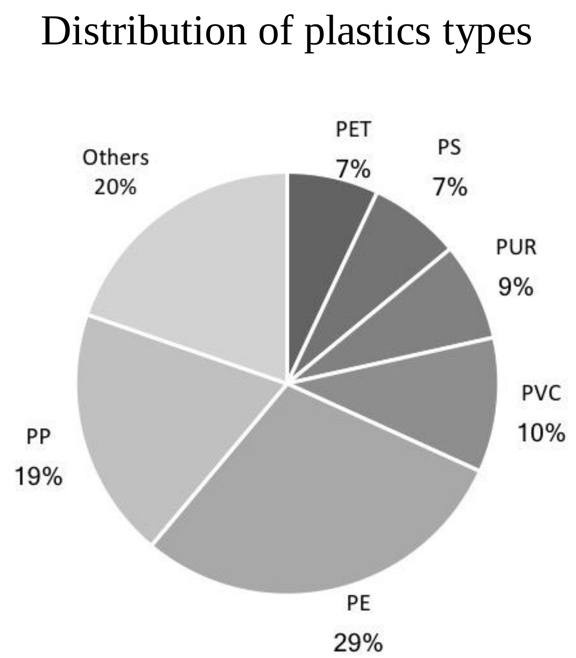

Figure 2: The distribution of the main types of plastics used in Europe showing that polyethylene (PE) is the most common plastic. Based on data from (Plastics Europe, 2016).

3.4 Manufacturing of plastic products

After polymerization the polymer films, pellets or granulate are blended with additives and formed into plastic products. The choice of additives depends on the purpose of, and demands on, the desired plastic product. Process-aids can make the plastics easier to process and protect them from heat and shear forces. Specific pigments, such as carbon black, can also protect food in a package from aging by acting as a UV-absorber. Other additives help protect the product by making the plastics less sensible for impact, hindering it to crack if hit. Flame-retardants protect the product and the user (British Plastics Federation, 2017). However, the most commonly used additive are mineral fillers that are less expensive than the polymer and save plastics feedstock (Lundgren, 2017).

There are numerous fabrication methods for forming plastic products. Moulding and extruding are the most common. In moulding, plastic products are moulded into shape from a melt of plastics granulate. All thermoplastics can be used as raw material and the products are of widely different types; high precision requirements such as special medical components and also every-day objects that are produced in large numbers such as cups, cutlery etc. In the extruding process the plastics are pressed through a nozzle to create plastics objects of a fixed cross-sectorial profile like for instance wastewater pipes (Plastics Industry, 2017).

The European plastics manufacturing industry consists of around 60 000 companies employing around 1.5 million employees and it was estimated to have an annual turnover of 350 billion euros in 2016 (Plastics Europe, 2017). In Sweden, there are about 500-600 plastic product manufacturers of which most use either of the two most common fabrication methods: moulding or extruding. Moulding industries are often smaller companies and most of them have under 35 employees (Alm, 2017).

3.5 Renewable plastics

Plastics are not necessarily produced from fossil feedstock, in this section three renewable production routes are described. The term bioplastics often leads to confusion since it is an umbrella term for different types of plastics: bio-based and non-biodegradable, bio-based and biodegradable or sometimes even fossil-based (non-bio-based) and biodegradable. Currently, bioplastics represent below one per cent of global plastics production, with an annual production of 2.1 Mton. Demand is rising slowly, and new materials are entering the market. The predicted production by 2022 is about 2.4 Mton (European Bioplastics, 2017a). However, predictions are uncertain and varies a lot over the years depending on the development of a few large projects. The previous projection indicated a more than a doubled production of bioplastics by 2021 of about 6 Mton (European Bioplastics, 2016).

3.5.1 Bio-based non-biodegradable plastics

Bio-based and non-biodegradable plastics constitutes the largest share of the global bioplastics production. The annual bio-based plastics production is around 1.2 Mton and it is predicted to grow to about 1.4 Mton by 2022 (European Bioplastics, 2017a). As with the general case described above, previously expected production increase was much larger. Nevertheless, the bio-based plastics would still only account for a few percent of the global plastics production with the current projections (European Bioplastics, 2016).

The dominating bio-based plastics are drop-in polyethylene used for example in milk cartons. The production of bio-based polyethylene from sugarcane starts with synthesis of ethanol by a fermentation process from sugars followed by a chemical dehydration transforming ethanol into ethylene. The polymerization then takes place via poly-addition as described earlier. Bio-based polyethylene is chemically identical to fossil-based polyethylene and therefore has the same technical properties. Partly bio-based PET is produced commercially by using bio-based ethylene glycol, one of the monomers building PET. The other monomer, terephthalic acid, is still fossil-based. However, development of commercially viable routes to produce bio-based terephthalic acid is being attempted (Voevodina and Kržan, 2013). There is also a growing interest in 2,5-furan dicarboxylic acid (FDCA) to make PEF as a possible and fully bio-based substitute for PET. PEF is denser than PET and are a better oxygen, carbon dioxide and water barrier (Horizon 2020 Projects, 2017; Avantium, 2018).

The concerns pointed out in relation to sustainability of the bio-based plastics are aspects related to intensified farming, increased utilisation of water and fertilizers, the risk of deforestation, reduced biodiversity and increased greenhouse gas emissions due to land use changes (Mülhaupt, 2013). Land for biomass production is a scarce recourse but efficiency development and synergies with agriculture and forest sectors could manage a sustainable development (IPCC, 2012; Brodin et al., 2017; European Commission, 2012; Niewöhner et al., 2016). Notable are that similar considerations for sustainability are not applied to fossil-based plastics.

3.5.2 Bio-based and biodegradable plastics

Besides the above described production of bio-based, non-biodegradable plastics, there are also bio-based biodegradable plastics. Biodegradable plastics production is smaller than that of bio-based non-biodegradable plastics but are expected to grow at the same rate, from 0.9 Mton in 2017 to 1.1 Mton in 2022 (European Bioplastics, 2017a). The properties of biodegradation do not depend on the feedstock, but on the chemical structure of the polymer. The recent development of bio-based plastics from the 1990th up till today, all started with development of biodegradable plastics (Scharathow, 2012).

Among the bio-based biodegradable plastics, polylactic acid (PLA) is the most common. PLA is an aliphatic polyester that can be produced by fermentation of sugars and starch to lactic acid, which is converted to lactide, a cyclic dimer of lactic acid, which is then polymerized into PLA. PLA has properties comparable with those of classical thermoplastics and is used in application such as packaging materials, disposable dishes, sheets, fibres, etc. Since PLA can be broken down to un-harmful monomers that are assimilated by the human body it has also been used in certain medical applications (Voevodina & Kržan, 2013).

Starch blends are also among the largest groups of bio-based biodegradable plastics. Starch is a natural polymer and has the highest biodegradability compared to the other biodegradables, but has poor processability, stability and mechanical properties for many applications. To be an attractive raw material in plastics production starch is blended with some synthetic degradable polymers like aliphatic polyesters (PLA, PHA) but it can also be blended with olefins to an only partially degradable product. Starch can be converted to cellulose derivate by a reaction with the hydroxyl group in the starch molecule into a raw material with properties that differ significantly from the parent starch but with maintained biodegradability (Lu et al., 2009).

Biodegradable plastics is a topic under debate. Biodegradables are described as a material that bring opportunities as well as risks. They can certainly have a role in some applications, but further development is needed. Most biodegradable plastics of today need special conditions to degrade and may not degrade in nature. Biodegradable plastics can intentionally and unintentionally, encourage littering, due to consumer behaviour and misunderstandings. Innovation on materials that fully degrade in water and are harmless for the environment and ecosystems are pointed out by the EU in the Plastics Strategy as extra interesting (European Commission, 2018a; European Commission 2018b). There is a risk that biodegradable plastics are introduced instead of tackling the challenges related to waste management (European Commission, 2018a; Quecholac-Piña el al., 2017). Oxo-degradable plastics, which only degrade to microplastics, can be mistaken for biodegradable plastics (Cornell, 2007; European Bioplastics, 2017b; European Commission, 2018b). Furthermore, the mix of biodegradables into the flow of plastics material for recycling raises concern among recyclers (Dagens Samhälle, 2016; European Commission, 2018a).

3.5.3 Plastics from other renewable sources

Biomass is not the only possible renewable feedstock for a non-fossil plastics production, another potential alternative is using methane or carbon dioxide, hydrogen and renewable electricity. Producing plastics from carbon dioxide would mean converting a greenhouse gas to a valuable raw material. Various initiatives and companies are developing processes aiming in that direction. Covestro are currently developing a polyol, a platform chemical that can be used in for example mattresses. Production is still small (Covestro, 2017). Another example is the production of PHA from methane claiming that it can replace various thermoplastics in most manufacturing processes (Newlight, 2017).

The production process varies, but in principle the carbon in the carbon dioxide, together with hydrogen from water and renewable electricity, can form any basic chemical needed for a plastic. One example is producing the worlds most used plastics, polyethylene, via methane as illustrated in the scheme below.

$$\text{Carbon dioxide } (CO_2) \text{ and Hydrogen } (H_2) \rightarrow \text{Methane } (CH_4) \rightarrow \text{Monomer } (C_2H_4) \rightarrow \text{Polymer (PE)} \rightarrow \text{Plastic product}$$

Biogenic carbon dioxide in pure streams may be limited, but in contrast to biomass there are no resource constraints on carbon dioxide and renewable electricity in general (IPCC, 2012). One opportunity is integration with the energy system, for example via using excess renewables for production of hydrogen. However, using a renewable, and possibly sustainable, carbon feedstock also has its drawbacks. The process is energy intensive and the end-product originating from carbon dioxide is therefore expected to have a three or four times higher cost than the current plastics (Palm et al., 2016).

4 Plastics consumption

The magnitude of the plastics consumption has great influence on the sustainability aspects of the plastics system. The amount of plastics being consumed influences utilization of feedstock, energy and creation of waste. However, a reduced use of plastics might not lead to lower environmental impact. There are several examples where plastics contribute to a more efficient use of resources. First, plastics are lightweight making transportation more efficient. Second, plastics are durable which has the potential to reduce the need for resources. Third, plastics decrease food waste in the modern global food-supply-chain. Nevertheless, unnecessary and unsustainable plastics consumption also needs addressing, especially in low value applications. Since plastics are used both in low and high value applications, there is a risk in equating all types of plastics consumption as unsustainable. The main challenge related to consumption is perhaps increasing the resource efficiency.

4.1 Key figures of plastics consumption

The global consumption of plastics has grown ever since plastics entered the market in the 1950s. In the past 50 years, the utilization has increased twenty-fold and the projection for the coming 20 years is that it will double. Globally over 335 Mton of plastics are produced annually, in the EU the corresponding number is 60 Mton (Plastics Europe, 2017). Much of the plastics in the EU are used in long-lasting applications such as construction (20 %), automobile (9 %) and electronics (6 %), see Figure 3. The largest category of use for plastics produced in the EU is single-use applications such as packaging (40 %) (Plastics Europe, 2016).

A mapping of the Swedish plastics system shows that about 100 kg/capita of plastic are consumed every year, and the distribution between the consumer categories are similar to the EU. Packaging is the by far biggest category (39 %), thereafter follows construction (21%), automobile (8 %) and electronics (6 %) (SMED, 2012).

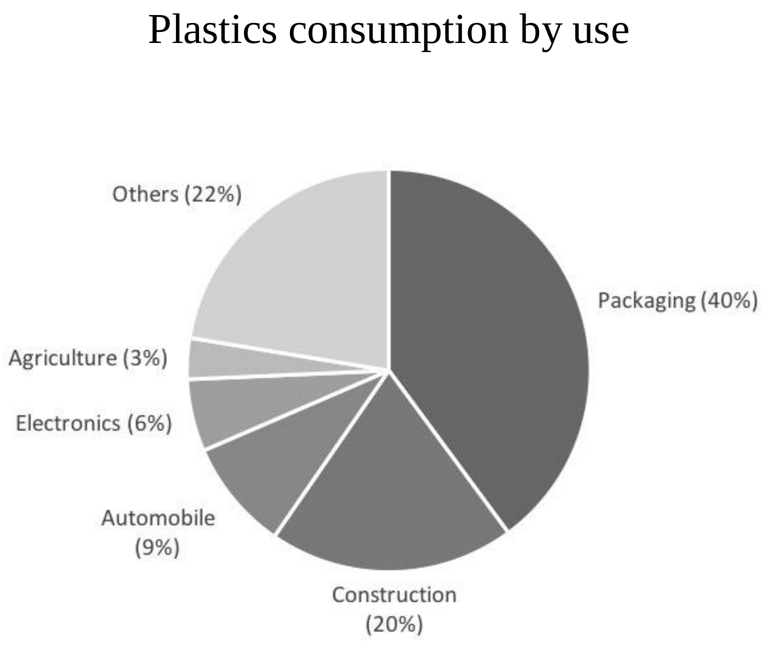

Figure 3: The distribution of the plastics material demand by categories in the EU 2016. Based on data from (Plastics Europe, 2016)

Given the high rate of plastic consumption in single-use packaging, one could argue that almost half of all plastics is only used once and for a short period of time, which is essentially a waste of resources. However, this is only true for the end-consumer of the product. Considering the value chain and life cycle of the packaging other aspects such as keeping the product fresh, maintaining the clean surface during manufacturing and transportation are highlighted. An important aspect of a sustainable plastics system is therefore resource efficiency, aiming at a more strategic use of plastics.

4.2 Policies on plastics consumption

Due to the range of environmental issues related to plastics there is an increasing interest to govern plastics all around the globe. One of the first and most well-known policies is the ban of plastic bags in Bangladesh (Bangladesh Environment, 1995). After several floods caused by plastic bags clogging the water infrastructure, the ban was introduced. Since then, many countries and cities have followed and implemented various policies for plastic bags (Xanthos and Walker, 2017). What they all have in common is that they focus on solving consumer related plastics littering, via a ban of what is regarded as a big littering issue (Convery et al., 2007; Klar et al., 2014). Other sustainability issues such as the fossil content of the product or its impact on the climate are often not regarded.

The EU has followed this global trend on introducing policies for plastic bags. The EU target is divided in two options, either the consumption of plastic bags should be reduced to 90 bags per person/year by 2019 and 40 bags per person/year by 2025, or no bags should be handed out without a charge by 2019 (Directive EU2015/720). Sweden has therefore implemented a new regulation for plastic bags. The plastic bag utilization in Sweden is relatively low, therefore the first step has been to impose information. The regulation obliges all providers of plastic bags to inform the consumers about the environmental benefits with a decreased usage of plastic bags and inform about the benefits of other alternatives and general measures for a decreased plastics consumption. The policy was implemented in Sweden on June 1th 2017 (SFS 2016:1041) and in the first three months, the policy had resulted in 2.5 million less plastic bags being consumed (Naturskyddsföreningen, 2017a). For a plastic bag with an estimated weight of 15-17 g, this corresponds to a reduction of plastics use of about 40 tonnes.

Recycling targets are also a common type of plastic policy, aiming at consumers to sort plastics in the recycling bin rather than in the general household waste. The collection rates of plastics vary within the EU, this not only depending on consumer behaviour but also on the level of recycling infrastructure (European Commission, 2016). The value losses in the current recycling system implies that policies for increased recycling should not only be limited to governing of the consumers, but also of the plastic system (Material Economics, 2018). A wider EU governance that effects all economic sectors, including the plastics system, is the EU circular economy package. The package sets targets on both reduction of waste and on consumer related recycling.

Only parts of the collected plastics are recycled into new products, depending on factors such as conversion rates in the separation facilities and low market demand for many of the recycled plastics. This is addressed in both the EU Plastic Strategy and the Waste legislation. Efforts are made not only towards improving consumers recycling habits, but also towards decreasing consumption and minimizing waste and littering (European Commission, 2018a; European Commission, 2014a). Considering efforts to reduce plastics in the environment, it should be noted that the majority of plastic waste present in the oceans is not derived from Europe. It originates from costal countries and rivers outside in counties with lacking or poorly functioning waste management systems such as: China, Indonesia, Sri Lanka and The Philippines (Jambeck et al., 2015).

The issue of consumer awareness is addressed by different actors in the plastics system. One strategy is to increase the incentives for consumers to recycle plastics, via raising awareness and educational programmes (European Commission, 2017a). There are misconceptions on plastic waste, recycling and the consumers' responsibility regarding recycling. For example, in Sweden more than 70 % are not aware that they are obliged by law to sort their waste at home (Konsumentföreningen Stockholm, 2017).

Policies addressing reduced consumption and reduced resource use are not being implemented on a wider scale, and by some this is considered to be a key issue (Naturskyddsföreningen, 2017b). Instead there are policies targeting smaller applications of plastics, such as microplastics in cosmetics (Regeringen, 2018), plastic bags (Regeringen, 2016), and finances provided for cleaning the shores from plastics (Naturvårdsverket, 2016).

4.3 Reduced and increased use of plastics

Plastic is an omnipresent material and most consumers and companies have a relationship to it. Feelings are often strong around plastics and there seems to be two competing trends claiming sustainable use of plastics, either by increasing or reducing the use of plastics. The two trends are explored below.

The reduced use of plastics occurs mainly on smaller scale, such as private households, kindergartens and plastic-free grocery stores, but there are also governmental initiatives on for example banning microplastics in cosmetics (Miljö- och Energidepartementet, 2017). In Sweden, the phenomenon started on a wider scale in 2014 resulting in that the word "plastbanta" (approx. plastic diet) was introduced on the words-of-the-year-list (Nyordslistan, 2014). The driving force for those living with a "plastics diet" is to decrease the exposure of chemicals present in some plastics and to avoid the health effects associated to other types of pollution (Landrigan et al., 2017). The focus is mainly on kitchen tools and children toys, and the main group of practitioners are families with small children and kindergartens (Fall and Tell, 2015). Another similar trend is the plastic/package-free grocery stores popping up in gentrified areas in European cities; providing (often local or sustainably produced) bulk products without packaging. The motivation behind this is to provide the opportunity for environmentally concerned consumers to reduce both food and packaging waste (The New York Times, 2016). Even though research show that microplastics and potentially hazardous chemicals are present in marine organism (e.g. Wright et al., 2013), it is argued that focusing a plastic diet on specific food products risk being unbalanced. Recently published research show that the exposure of additives and microplastics is higher from the general consumption of plastics than from specific food or drinks, and therefore the discussions should focus on the general human exposure of plastics (Rist et al., 2018). Reducing waste and reducing the exposure of potentially harmful chemicals are trends that decrease the use of plastics under the umbrella of both environmental and social sustainability.

The impact of these initiatives is probably quite small in scale, but nevertheless representatives of the plastics industry are concerned with the consumers increasing scepticism towards plastics and the trends of decreasing utilization. In order to increase the credibility of plastics being a sustainable material, the industry focuses on topics such as recycling, prevention and recuperation of marine litter, circular economy, increased awareness of the sustainability aspects of plastics etc. (e.g. IKEM, 2017; Plastics Europe, 2017). There are also attempts to handle the trend of "plastics diets" and flourishing misconceptions on plastics (Plastteknik Nordic, 2017).

The trend in increasing plastics use is much stronger. Heavier and more expensive materials are being replaced by mouldable and less expensive plastics material. The trend in increasing use appears in production of aeroplanes and cars, where plastics and other polymers are widely used. Plastics has the advantage of being durable, strong and lightweight and therefore decreases the weight of the vehicle and thereby the consumption of fuel. Airplanes nowadays can contain of up to 50 % reinforced plastics and other composites (including bio-based materials), which is claimed to reduce the weight by 20 % compared to the previous aluminium design (Boeing, 2017). Also, lightweight plastics packaging decreases fuel consumption in the distribution chains.

4.4 Business consumption

Discussions on decreased and/or improved plastics consumption tends to be driven by consumers, but many of the decisions affecting sustainability are taken earlier in the value chain. Furthermore, a great part of the consumption also takes place between and within companies. Perhaps it is within the business consumption of plastics that the opportunities lie for initiating a sustainability transition of the plastics system?

Some companies take a proactive position. Especially companies that have products close to the end-consumer, such as plastic bags, food packaging and furniture (e.g. Tetra Pak; Polarbröd; IKEA). Currently companies working with mainly renewable or recycled plastics do so due to a clear business vision. In those cases, the potentially higher cost of the feedstock is not considered a hinder, and the clear environmental vision seems to be the key driving force (Soesanto et al., 2016).

A clear vision of sustainable plastics is not enough. Among the companies that have a high ambition to use bio-plastics or recycled plastics, one problem is feedstock availability. IKEA has an ambition to use 100 % renewable and/or recycled plastics in the series of interior design by 2020. Despite their broad market search, looking at recycled, carbon dioxide and bio-based materials, there appears to be a lack of feedstock (Röhne, 2016).

Initiatives towards sustainable feedstock is also addressed higher up in the value chain. Some of the world's biggest chemical companies (e.g. DuPont, Braskem, BASF) are exploring the prospects of expanding the production of bio-based plastics. They have chosen different paths, but all have identified business cases and market opportunities for more sustainable plastics (Illes and Martin, 2013; Avantium, 2018).

Behavioural changes are a challenge in the business development of more sustainable plastics, influencing both the consumers and the product developers. The recent political and environmental issues connected to biofuels and biomass feedstock has developed a fear amongst product developers to explore renewable material options. Even though the product developer has a personal conviction on the importance of sustainability, the risk of being accused of greenwashing impede the increased use of bio-based materials in their production (Brockhaus et al., 2016; Börjesson et al., 2008).

There are a number of initiatives within business consumption aiming at sustainability, but it can still be argued to take place on a niche scale. Companies of all sizes and places in the production chain want to explore the new market and be leaders in sustainability. However, there are obstacles both regarding feedstock availability and communicational- and knowledge aspects (e.g. fear of greenwashing).

5 Plastics waste management

Recycling of plastics can reduce the use of virgin feedstock and is therefore an important part of creating a more sustainable plastics system regardless of feedstock. Besides increasing the recycling rates, other issues includes reducing the amount of plastics in landfills and reducing littering.

Globally 40 % of the plastic waste ends up in landfill, 14 % is incinerated or energy recovered and only 14 % is recycled. Adding these figures together 32 % are unaccounted for. This indicates that 32 % of the plastic waste accumulates in society or nature. The recycling rates for plastics in the EU and Sweden are higher than the global average, but it varies greatly between countries (Neufeld et al., 2016). The same is true for plastics in landfill, where some EU countries (including Sweden) have a ban on putting recyclable material such as plastics on landfills resulting in that almost no plastics end up in landfills (Plastics Europe, 2017).

5.1 Legislation

Plastics recycling is regulated by numerous directives and regulations, both on an EU and a national level. The EU Waste Framework Directive 2008/98/EC is overarching and article 11.2a states that 50 % of the household waste should be recycled or re-used by 2020. Article 11.2b in the same directive, states that 70 % of the non-hazardous demolition and construction waste should be recycled or prepared for re-use by 2020. The largest plastic waste category is plastics packaging and in the Directive on packaging and packaging waste (94/62/EC) targets are set for recycling or re-use of packaging made of plastics. The targets are set as before and after 2008, and the current target is that 22.5 % of the plastic packaging waste are to be recycled to new plastic products. New targets are currently being negotiated.

Several EU waste Directives mandate or encourage the application of extended producer responsibility schemes (EPR) in which producers and importers of a certain category of products are obliged to finance and operate recycling systems for their products, with targets on recycling rates. Regarding plastics packaging, EPR schemes are widely used in support of the implementation of the Packaging and Packaging Waste Directive (94/62/EC), although the Directive itself does not impose the principle (Spasova, 2017). However, out of the 28 EU member states 27 have an EPR scheme for packaging (European Commission, 2014b).

End-of-life vehicle and electronic waste contains considerable amount of plastics, the waste management of this is governed at EU level. Article 8 in the Waste Framework Directive 2008/98 sets up principles regarding the implementation of EPR by the European Member States (European Commission, 2014b). EPR schemes for end-of-life vehicle is mandatory through Directive 2000/53/EC, and for waste from electrical and electronical equipment through Directive 2012/19/EU.

The Swedish legislation on producer responsibility for packaging (SFS 2014:1073) was introduced in 1994 and today it states that all producers and importers of packaging have the environmental responsibility for their products. They are obliged to collect and recycle the end-of-life packaging and report statistics to the government. The Swedish regulation on waste (SFS 2011:927) states that households and businesses are obliged to sort out packaging waste into the collecting system run by the producers. The Swedish EPR for packaging has a target of 30 % recycling and after 2020 it increases to 50 %.

In Sweden, the deposit system for some beverage containers is managed by the regulation on deposits systems for plastic bottles and metal cans (SFS 2005:220). This regulation does not include any recycling target, but there is a demand on the fillers of some beverages in plastics packaging to include the package in the deposit systems. However, PET-bottles in the deposit system have separate goals and statistics. The current recycling rate for PET-bottles under the deposit system is 83 % however the recycling target is 90 %. The recycling rate for PET-bottles has been almost constant since 2012, meanwhile the number of PET-bottles on the market has increased by almost 20 % (Naturvårdsverket, 2015).

5.2 Organisational structure

The producer responsibility is in theory an obligation for the individual actor, but producers often organize themselves in Producer Responsibility Organisations (PROs) to implement the EPR principle. The PROs have three main functions: first, to finance the collection and treatment of the targeted waste stream and redistributing the corresponding financing; second, managing the corresponding data and reporting; and third, organizing and/or supervising the activities (European Commission, 2014b).

The Swedish actors have started PROs together to shoulder the EPR responsibility. For plastics, it is named Plastkretsen (approx. The plastic circle), but in 2007 Plastkretsen merged with the other packaging waste PROs to one recycling organisation, Förpacknings- och Tidningsinsamlingen (FTI) (approx. The packaging and newspaper collection). FTI has the responsibility to develop and manage the systems for collection and reaching the recycling targets for packages and paper.

The EPR system is financed mainly through fees on packaging paid by the consumer, but also by the revenue that the sale of the recyclables to the recycling industry generates. The member companies share the cost of the collection system based on market share of their products (FTI AB, 2017a). Furthermore, the car manufacturing industry and the producers and importers of elecrical and electronic equipment have formed their own PROs, BilRetur (approx. returned cars) and El-kretsen (approx. electric circuit).

The municipalities have an overarching responsibility for planning the waste management in Sweden and are responsible for collection and treatment of the waste from housholds, and similar waste from businesses. The packaging that is not collected in the EPR system end up in the residual household waste stream of municipal waste. In general, about one third of the residual waste in the bin of a Swedish household consists of packaging and paper that are included in the EPR. Because of this many municipalites complement the producers collection system by door to door schemes for EPR materials (Avfall Sverige, 2016). This divided, and sometimes conflicting, responsibility of waste between municapialities and producers/importeres is highly debated in Sweden. It has been subject to many governmental reports and the legislated EPR for packaging has been questioned.

Recycling is more than just collecting the waste, the aim is to re-enter the material to the system as a new product. When the plastic waste has been collected by the PROs, they are responsible to set the material on the recycling market to reach the legislative goals. The sorted waste is sold to a recycling facility for washing and manufacturing of re-granulates or flakes. The material is then sold to manufacturers of plastic products to be used as recycled feedstock.

5.3 Plastics waste streams

In Sweden, a total amount of 558 000 tonnes of plastic waste is produced every year. Of this amount, more than half (298 000 tonnes) originates from households and consists of packaging, bulky waste, deposit bottles and other plastic waste. Of these 298 000 tonnes of household waste around 68 000 tonnes (23 %) are collected for recycling and 230 000 tonnes (77 %) are used in energy recovery. The largest portion of plastics household waste is packaging of which 46 000 tonnes is collected separately for recycling and 151 000 tonnes ends up in the household residual waste and is sent to energy recovery (SMED, 2012). The figures for household plastic waste as a whole is illustrated in the first bar in Figure 4. It can be seen that a small fraction of the plastics from waste electrical and electronic equipment and end of life vehicles end up in landfill. On the other hand, plastics from the agriculture sector is the category which has the highest rate of recycling. This is probably due to the uniform kind of plastics used and relatively few users. For medical applications, it is the other way around with many different types and often contaminated plastics, and all plastic medical waste is incinerated.

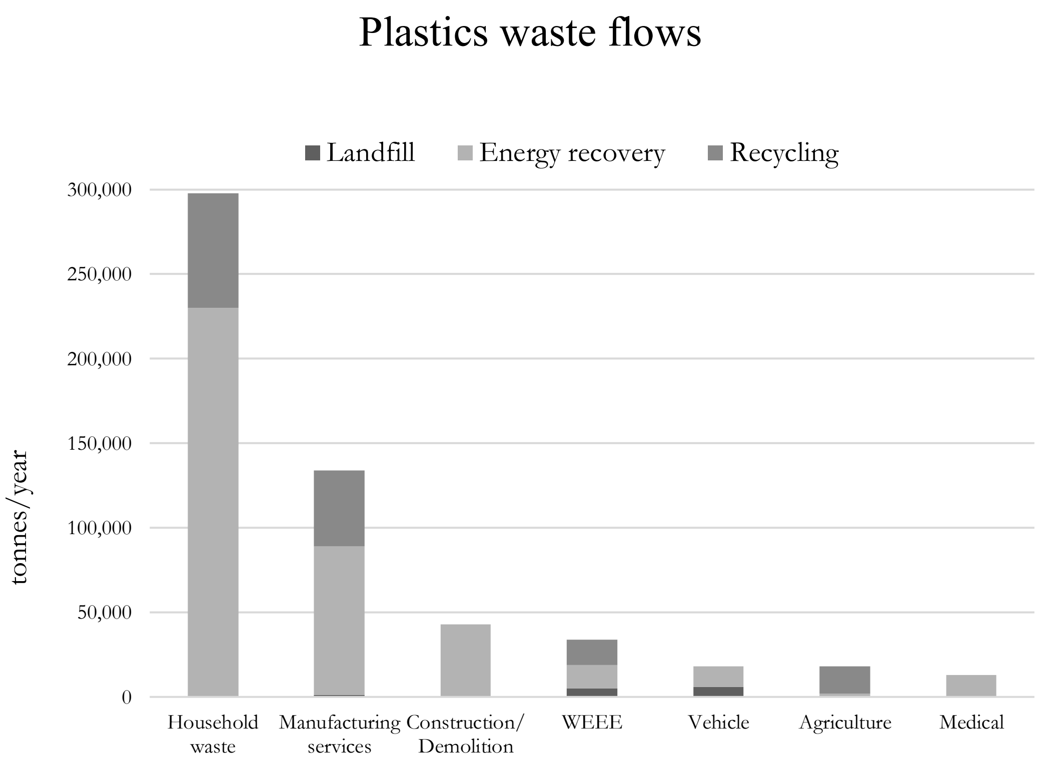

Figure 4: Waste handling of plastics in Sweden by category of treatment. Based on data from (SMED, 2012).

Bulky plastic waste like furniture, big packaging, buckets and toys, that are currently collected at municipal recycling centres could be collected in a separate waste stream. However, today many Swedish municipalities collect this bulky plastic waste within the fraction for energy recovery, since these plastics are not economically interesting for the recycling industry. According to SMED (2012) this flow is 39 000 tonnes per year.

It is important to be careful with numbers regarding plastics recycling. The numbers that are presented as recycled amounts of plastics, often present the collected amounts rather than the recycled amount. This can be misleading since there are losses in the sorting and preparation facilities that makes the amount of actually recycled plastics less than the collected amount. Plastic waste can be both plastics products in general or only plastics packaging and it can originate from households or from households and manufacturing combined. The statistics on capture rates can be built on either the amount collected as a share of the amount set on the market or as a share of the amount of plastics in the waste stream. One example is illustrated with the graph in Figure 5. The figures present the *degree of recycling* as the amount of *plastics packaging collected* divided by the *total amount of plastics packaging* set on the Swedish market. The decrease in recycling in 2010, is due to adjustments of the measurement methods. The adjustment included that the wrongly sorted plastics packaging was discarded from the amount of collected plastics. However, the figures do not show the losses in the following mechanical sorting. Nor do they show the losses in preparation for recycling in the recycling industry that are about 10-30 %, sometimes as high as 50-90 % (Avfall Sverige, 2017). These losses are incinerated, and not recycled.

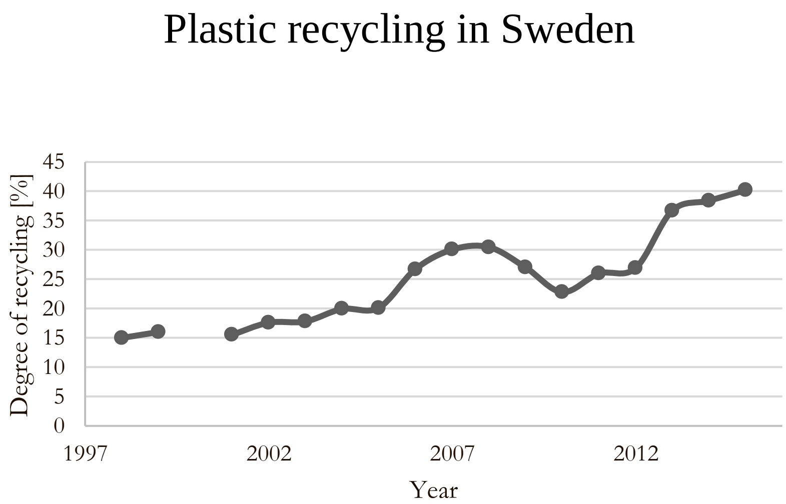

Figure 5: Share of plastics packaging recycled in Sweden based on statistics from FTI AB. The decrease in 2010 is due to new calculation procedures. Based on data from (FTI AB, 2017b)

Plastics recycling varies widely between countries and product groups. The ambitions are often set high by both the civil society and legislators, however relatively small amounts of recycled plastics are actually turned into new products. Plastics packaging waste show the lowest capture rate of the different kinds of packaging collected in households in Sweden (SAMSA, 2016). Furthermore, plastics are collected as just "plastics" even though, as described in Section 3.3, there is a wide range of different plastics. This creates a mix of plastics that is difficult to handle in the downstream recycling system.

5.4 Additives and recycling

Additives can, to different degrees, influence the recyclability of a plastic product and for the recycling system different additives have different kinds of consequences in the processes. The most common additives are fillers. The fillers often change the density of the plastics, and therefore decrease the yield in the recycling process where washing and separation of material is often made by density. Colour is another additive that has impact on recycling by affecting the demand of the recycled plastics material. The recycling stream is therefore separated in colourless and coloured. The colourless or lighter coloured plastics has a higher value then the coloured stream. Coloured streams are generally mixed together creating a grey or black re-granulate. A large group of additives are those which change the melt flow index, a measure of the ease of flow in the melted plastics. An important aspect when recycling plastics is to be able to separate different plastics according to their melt flow index (Snell, 2017). According to the plastic recyclers the heating in the recycling process does not clean plastics from additives. The additives are blended into the plastics at a high temperature and have the properties to stay in the plastics melt (Snell, 2017). One effect is that the mix of often unknown additives in recycled plastics might limit the usefulness of the recycled material.

6 Discussion

Plastics will probably have important functions in a future sustainable society. However, the current plastics system faces major sustainability challenges. There is no clear definition of sustainable plastics, but the starting point of this report and STEPS is that a more sustainable plastics system involves an increase in the resource and material efficiency of plastics consumption, a significant increase in the reuse and recycling of plastics and a switch to renewable feedstock. This report of the plastics system points out four major sustainability challenges that are described below. Furthermore, some potential solutions and conflicts between them are discussed.

6.1 Challenges

6.1.1 Renewable and recycled feedstock

The feedstock of today's plastics is virgin, fossil, relatively inexpensive and has well-defined quality and production properties. A challenge with switching towards renewable feedstock is that it might not have the same price or availability. Switching to recycled feedstock is currently associated with quality issues, since the original additives and chemical content often is unknown as a result of the mix of different kinds of plastics in the waste stream. Using carbon dioxide as plastics feedstock might be two to three times more expensive, due to the high electricity demand. Bio-based plastics could be less expensive, but faces the challenge of feedstock availability, potentially competing for limited arable land with food production and a growth in bio-based fuels (IPCC, 2012).

6.1.2 Resource efficiency

Efficiency does not per definition imply a decrease in consumption; an efficient use of plastics can involve using more plastics, but without consuming more resources. If plastics are designed to enable increased reuse and recycling, then the consumption of the feedstock will be minimized. The use of plastics can also lead to improved sustainability since the environmental benefit of food packaging, lightweight transportation, and material substitution can be greater than the environmental drawbacks. On the other hand, a decreased use of plastics would decrease the dependence on fossil feedstock and possibly lead to decreased littering. Regardless of the trade-off, it is certain that resource efficiency will be important in a future sustainable plastics system.

6.1.3 Waste management and recycling

Currently the generation of plastic waste is closely linked to economic growth, therefore it is important to address waste minimization and recycling to reduce the environmental impact. Recycled material for feedstock is not yet an economically competitive option. However, in a fossil-free future the renewable feedstock is likely to be more expensive, and plastics could therefore become more attractive to recycle from an economic perspective.

Polypropylene and polyethylene are relatively easy to recycle and are common in the biggest plastic waste flow, namely the post-consumer plastic waste. Nevertheless, plastics show the poorest recycling rates compared to other materials and it should be noted that only post-consumer PET can be recycled back into food packaging. Some of the challenges connected to post-consumer plastics are that they contain a mixed stream of plastics of different kinds, colours, additives, composites etc.

6.1.4 Plastics leakage

The increased use of plastics has resulted in an increased amount of littering, both on land and in the oceans. Developing waste management systems can therefore contribute to a reduction of the plastics littering. Although an increased recycling is desirable, no system can be completely circular and there will always be losses and diffuse leakage of plastics from society, such as from car tires and clothes washing.

Since plastics are fairly stable materials, all plastic waste that is not collected within a waste management system, ends up somewhere and degrades slowly. Handling the global plastic littering issue is a big challenge and an essential part in achieving a sustainable plastics system.

6.2 Conflicts

The sustainability challenges of the plastics system are complex and the proposed solutions all have downsides, creating conflicts between different goals and potential solutions.

For instance, a transition towards a bio-based feedstock could limit the impact plastics has on the climate. However, an increased utilization of biomass for plastics may cause a strain on resources and cause conflicts between production of feedstock and production of food, feed or fuel. This conflict has partly hindered the development of biofuels in the EU and it might also hinder the development of bio-based plastics (Brodin et al., 2017; Niewöhner et al., 2016; Börjesson et al., 2008)

Another conflict regarding the sustainability challenges of plastics concerns littering and the durability of plastics. It is sometimes suggested that biodegradable plastics could be part of the solution to land and ocean littering. However, the biodegradables of today often demand special conditions to degrade and therefore, they risk not being fully degraded if they end up in nature. Biodegradable plastics bring opportunities but also risks and biodegradables can fill an important role in some applications in the future, but innovation and development is needed. Furthermore, biodegradable plastics are argued by the recycling industry to cause quality issues if they are mixed into the stream of plastics aimed for recycling and there is a need for clear labelling and also waste treatment facilities for biodegradables and recycling, respectively (European Commission, 2018a).

One way to increase recycling could be to limit the different types of plastics through regulation and standardization. However, this would on the other hand limit the possibilities for innovations of new materials and then possibly slow down the sustainability transition.

6.3 Ways forward

Plastics are a desirable material and therefore policies that improve the plastics system are needed. The main challenges have been identified and defined, but potential solutions are contested and still in emergent phases. There is no common vision of a desirable future plastics system, but both general and specific policies are explored.

6.3.1 General plastics policy

The European Commission has developed a Strategy for Plastics in a Circular Economy that defines sustainability issues with the current plastics system. First, the strategy points out the low rates of recycling and reuse of plastics. There are low economic incentives for recycling and reuse of plastics and also low recyclability of products due to the design of plastic products. The European Commission identifies a lack of governance approaches towards recyclability and towards design for recyclability. Second, the significant leakage of plastics to the environment is highlighted. The consequences of plastics littering are unknown, but as an act of caution, reduction targets are set in the Circular Economy Action Plan. Additionally, the strategy points out that there is a need for a clear sustainability framework for biodegradable plastics (European Commission, 2018a).

A starting point in driving the development of the plastics system in a more sustainable direction could be to introduce taxes, feed in tariffs or quota systems for the feedstock. The fossil feedstock in the petrochemical industry is currently neither taxed nor included in the EU Emission Trading System (EU ETS). In order to drive change the fossil content in plastics could be taxed just like the case with fossil fuels. Another option to initiate a sustainability transition could be to create a quota system where a share of non-fossil carbon could be required in plastics.

6.3.2 Specific policies for specific plastics

The word plastics include several hundreds of different materials, but in legislation, politics, and waste management, plastics are basically thought of as one material. One potential way forward is to consider plastics as different kinds of material with specific properties that require unique policies.

In the household waste stream, there are a mix of many different plastics. The households cannot be asked to separate them all, but perhaps the separation of plastic waste can be divided in two or three main streams for further sorting or treatment. This change could be driven by a specific policy for this specific plastic stream.

The most complicated plastics to recycle are the post-consumer plastics collected in recycling stations, recycling centres or in door-to-door systems from manufacturing businesses and households; garden-furniture, toys etc. This stream of plastic waste contains some high value plastics that are mixed with more challenging plastics. To a large extent these plastics are incinerated today either right away or as a reject from the post-sorting facility or recycling industry. Today's source sorting of a mixed plastic waste stream does not seem to be effective. One option could be to develop new deposit system (like the one for PET beverage container) that include other types of products containing mainly one recyclable plastic, such as polyethylene (PE) or polypropylene (PP).

Composite and multi-layer packaging are currently hard to recycle due to their material properties. A specific policy could either force multi-layer packaging to be bio-based to lower the climate impact when incinerated or could target the development of chemical recycling. Chemical recycling is a technology that turn plastics into their chemical buildings blocks. These can later be separated by molecular size and enter the plastics production process again. The idea is that chemical recycling would improve quality issues connected to the current mechanical recycling systems. Specific policies that targets plastics that are currently hard to recycle, could possibly create new incentive for chemical recycling.

One last example of a possible specific policy for a specific application addresses the issue of plastics leakage. In some applications the utilization of plastics almost inevitably involves a leakage to the environment, in those cases bio-degradable plastics could be part of a future solution. Besides the examples already mentioned, clothes in bio-degradable plastics could be considered due to the microplastics that are released when they are washed. However, this requires enormous development of the biodegradability properties in different types of marine environments.

6.3.3 Forerunners

The plastics system involves a great number of actors with different roles in a sustainability transition. Who are the forerunners in the current plastics system and where are the driving forces? Are the current governmental initiatives in form of new policy and legislation the start, or will it be initiated by small start-ups that are ahead in terms of meeting customer demands? Other potential forerunners are the global manufacturing giants, either as producers or users of plastics raw materials, or big plastic consumers such as municipalities using the power of public procurement.

Today the sustainability transition seems to start from big producers of disposable packaging and other consumer products, for example the Swedish milk container with bio-based polyethylene. However, initiatives are also taken from big consumers by coordinated public procurements like the procurement of disposable aprons made of mostly sugar cane, starch and lime in Region Skåne (Region Skåne, 2016).

6.4 Final words

Plastics is a lightweight, durable and flexible material. The properties of plastics make it a desired material in a wide range of applications; in consumer products, as vital parts in construction, in technical equipment, for health care and in packaging. Using plastics can thereby contribute to an increased sustainability.

However, the complex challenges connected to a sustainable plastics system must be overcome. Plastic waste - a flora of different kinds of plastics - must be reused or collected and recycled to a much higher degree than today. Product design both on molecule and product level could become most important. The plastics leakage must be understood and solved to decrease the potential damage that microplastics and plastics debris have on the ecosystems. And last but not least, in a decarbonised future the fossil feedstock of plastics has to be changed to a renewable and/or recycled feedstock.

The challenges are multi-dimensional and cannot be addressed one at a time. In the search for solutions collaboration between a wide range of academic disciplines will be essential. Furthermore, innovation, awareness and strong efforts from industry, consumers and policymakers from across the value chain are needed to create a sustainable plastics system.

7 References

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