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## Mid-Term Map of Availability of Plastic Wastes Across Europe

Deliverable 9.7 (v1)

WP9 Market Analysis, Exploitation and Business Plan

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## EXECUTIVE SUMMARY

The use of plastics in modern society is ubiquitous. Plastics play a pivotal part in human life as they are cost-effective, useful and versatile materials. The growth of plastics use has however had unfortunate consequences, the most visible of which is the unlegislated loss of plastics to the environment leading to huge volumes of plastics that have ultimately ended up in the Earth's oceans. Therefore, plastics have been reported as one of the major pollutants among various pollutants that are disposed of in the environment.

Currently, the life cycle for a majority of plastics used conform to a linear economy approach, whereby the plastics are produced, used once and discarded, which have become known as single-use plastics. Strategies to prevent loss of materials resources and damage to the environment are elements of a circular plastics economy that aims to maintain plastics at their highest value for the longest time possible and at the same time improve the economy and prevent detrimental environmental impact. The achievement of a circular economy will require not only innovative technical developments, but also major economic investment and changes to business practice coupled with significant changes in social behaviour.

The current study (Deliverable 9.7) complements the initial report on mapping of plastic waste in Europe and provides additional new information/data on EU plastics market and waste management. Specifically, the mapping covers EU plastics market, PU and PA production and market demands, application segments for PU and PA polymers and their main waste stream sources. In addition, common end-of-life strategies of different types of PU and PA products based on their nature and application area are discussed.

Global production of plastics was about 368 MT in 2019, of which 57.9 MT Plastics were produced in Europe. Packaging with 40% was the major demanding market for plastics, followed by building and construction (20%), and transportation (10%). Total production of polyurethane products is reported to have been 6.52 MTs in 2019, showing a slightly increase compared to 2017. However, the COVID-19 consequences are likely to cause a dramatic fall in production of polyurethane products in 2020, with some end-use industries like automotive sector suffering more than others.

Global production of polyamides exceeded from 9 MT in 2019, from which PA fiber and films held the major share of 55%. PA6 and PA66 made up most of the PA market. The share held by PA specialties, such as long-chain PAs is still small, despite the continuation of relatively high growth rates. Automotive engineering as well as electrical and electronics are major technical PA application industries.

It is also expected that polyamide demand in Europe will fall by 22% from 2019 to 2020 as a result of the coronavirus and the weakness in the European polyamide market will continue for the rest of this year.

29.1 MT of plastic waste collected for further treatment in the EU28+NO/CH, and plastic waste exports outside the EU have decreased by 39% from 2016 to 2018. Significant progress in diverting plastics away from landfilling has been made during recent years and plastic recycling grew by almost 100% between years 2006 and 2018. Landfilling and incineration are still the main practices for PU and PA wastes in Europe, despite existing mechanical and/or chemical recycling solutions.

In summary, the following information will be presented in the report:

- Plastics market and the main market segments of PU and PA in Europe

## D9.7 Mid-term Map of Availability of Plastic Wastes Across Europe

- Identification of polyurethane and polyamide waste streams and their share to total solid waste production in Europe
- Analyse the waste treatment processes and current developments for recycling of PU and PA waste

The current report is a mid-term report and might be subjected to an update and modification in the course of the project. The final report (Deliverable 9.10) will be submitted in month 42.

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## OVERVIEW OF THE DELIVERABLE

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WP: 9 Market Analysis, Exploitation and Business Plan

Task: 9.2

Title: Map of availability of plastic wastes across Europe

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General description of the deliverable, as in the DoA, describing:

- This task aims to provide an overview of the plastic waste materials generated in the targeted value chains, interesting candidates to be recycled by means of the innovations developed within the project.
- Innovations 1 and 2, focused on chemical recycling and upgrading respectively, will be focused on engineering polymers which are high-value added materials. Due to high-value of materials, supply will focus on sectorial scrap to avoid contamination and heterogeneity. Additionally, a mapping of the post-consumer wastes for these materials will be also carried out for a better understanding. Innovation 3 is focused on low-value plastic wastes such as mix-plastic waste (mainly based on polyolefins) and composites. Thus, a mapping of waste managers having these residues will be made in order to identify their distribution across Europe and their availability.
- In order to evaluate economic viability of the recycling process it will be also studied current approach used for waste management (recycling, energy valorisation, landfill...) that could compete with innovations. This economic information will be also shared with the economic assessment during LCC in WP8 will allow analysing the economic feasibility of recycling process for different wastes.

## LIST OF ABBREVIATIONS AND ACRONYMS

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CAGR – Compound annual growth rate  
CASE – Coatings, adhesives, sealants and elastomers  
EfW – Energy for Waste  
ELV – End-of-Life vehicles  
EMEA – Europe, Middle-East & Africa  
EoL – End-of-Life  
EU – Europe  
GNP – Gross National Product  
GRS – Global recycled standard  
HDPE – High density polyethylene  
HMDA – Hexamethylenediamine  
ISOPA - Manufacturers of aromatic diisocyanates and polyols  
KT – Kilo tonnes  
LCPA – Long-chain polyamide  
LDPE – Low density polyethylene  
LLDPE – Linear low density polyethylene  
MDI – Methylene diphenyl diisocyanate or diphenylmethane diisocyanate  
MDPE – Medium density polyethylene  
MSW – Municipal Solid Waste  
MT – Million tonnes  
NCO – Isocyanate functional group  
OBS – Oriented strand board  
OH – Hydroxyl group  
PA – Polyamide  
PE – Polyethylene  
PET – Polyethylene glycol  
PS – Polystyrene  
PU – Polyurethane  
PU/PIR – Polyurethane/Polyisocyanurate  
PUF – Polyurethane foam  
PVC – Polyvinylchloride  
RDF – Refuse derived fuel  
RIM – Reaction injection molding  
SME - Small and medium-sized enterprises  
TDI – Toluene diisocyanate or methylbenzene diisocyanate  
USD – US dollar  
UV – Ultra violet  
WEEE – Waste Electrical and Electronic Equipment

# 1 INTRODUCTION

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Plastics clearly constitute an important component of the range of materials used in modern society. Their broad diversity in terms of composition and processing techniques allows them to be used in a great variety of efficient applications. However, it is exactly this diversity that makes them challenging at end-of-life.

However, improving recycling, promoting reuse, and redesigning plastic products, and taking into account the whole life-cycle of products would accelerate creation of a circular economy for plastics.

POLYNSPIRE project aims to increase and improve recyclability of plastics by developing innovative recycling technologies, in which the overall objective of WP9 is to ensure the exploitation and commercialization of all the knowledge and technical results obtained from the execution of the previous WPs to pave the way for market uptake of POLYNSPIRE solutions for the targeted polymers along the value chain stakeholders and around Europe.

This will be achieved through the specific objectives below:

- To analyse market potentials, applications perspectives, risk and opportunities for the implementation of POLYNSPIRE solutions.
- To generate a business plan to commercialize the project results and to penetrate POLYNSPIRE in Europe's industries.
- To assess all the issues related to the creation of the necessary infrastructure for the promotion of a mass market, with focus on regulatory barriers.
- To define the most appropriate strategy for the exploitation of the results and exploitation plan, with special focus on the IPR management among partners.
- To develop a holistic assessment on the replicability and upscaling of the developed solutions, as well as a roadmap for their large-scale implementation.

Within this work package, Task 9.2 is devoted to conduct mapping of availability of plastic wastes across Europe. The current report complements the initial report (Deliverable 9.2) which was submitted in months 12 and includes additional and updated information/data on plastics production, market and recycling.

The Deliverable 9.7 is divided into three different parts. Firstly, an overview of EU plastics market and main end-user application segments of polyurethane and polyamide polymers will be made in order to establish a background on production capacity and market demand. The second part will study the plastic waste streams, especially PE, PP, PU and PA waste streams, to evaluate available plastic wastes as interesting candidates to be recycled by means of the innovations developed within the project.

Finally, in order to evaluate economic viability of the recycling process it will be also studied current approach used for waste management (recycling, energy valorisation, landfill...) that could compete with innovations.

Due to the public condition of this document, the intended audience of the deliverable 9.7 is firstly each individual participant of the Project Consortium and secondly, stakeholders and private institutions.

## 2 PLASTICS MARKET IN EUROPE

### 2.1 GENERAL OVERVIEW

The prevalence of plastics in modern lifestyles is undisputable. Plastic is a versatile material that can be used in a wide range of applications, from simple single-use packaging to high-tech durable industrial applications. Over the last decades, plastics have been key enablers of innovation and have contributed to the development and progress of society. The global production of plastics has on average increased by about 9% per year since 1950 and in the last 50 years, plastic production has increased more than twenty-fold, reaching 368 million tonnes\* in 2019, and plastic production is estimated to double by 2036 and might even quadruple by 2050.



Figure 1. World and EU plastics production data [1].

Figure 2 presents global distribution of plastics production in 2019. The EU accounts for around 16% of world production. China produces more plastic than any other country, at 31% of global production.

In Europe, plastics demand from converters in the EU-28, Norway and Switzerland was 50.7 MTs in 2019. Demand expressed as tonnage of virgin resin processed by European converters by country is shown in Figure 3. The major plastic-consuming countries are Germany, Italy and France which together account for around 47.5% of the EU market of converters to plastic products [1].

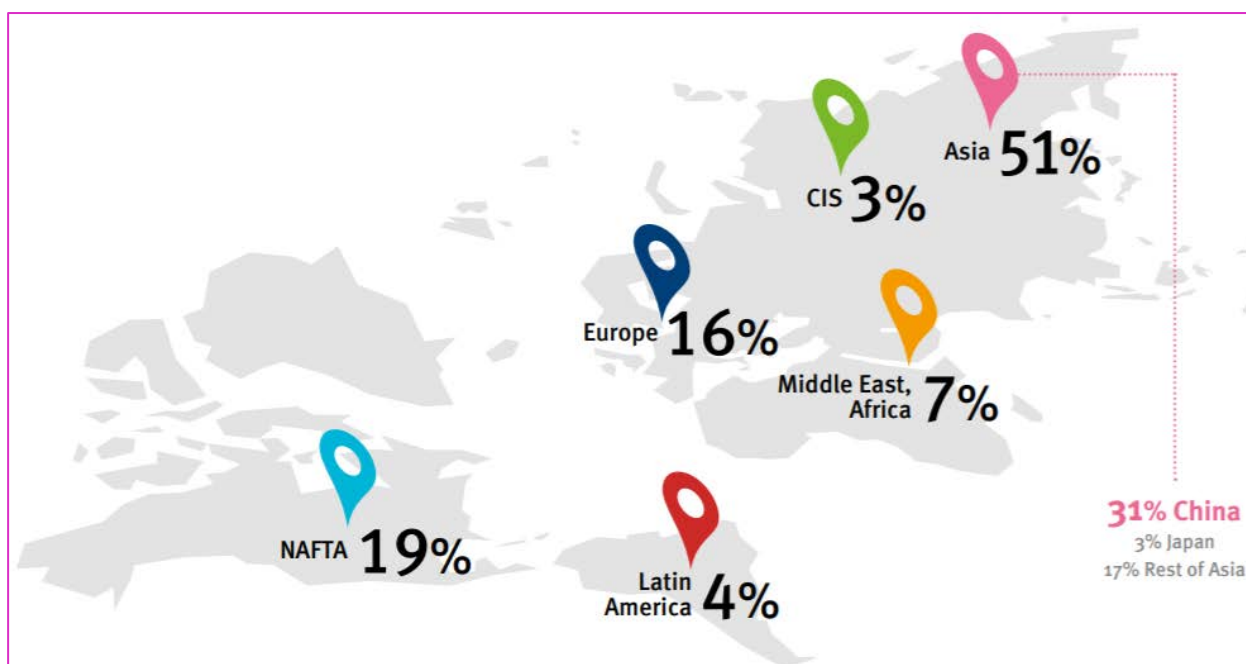


Figure 2. Distribution of global plastics production [1].

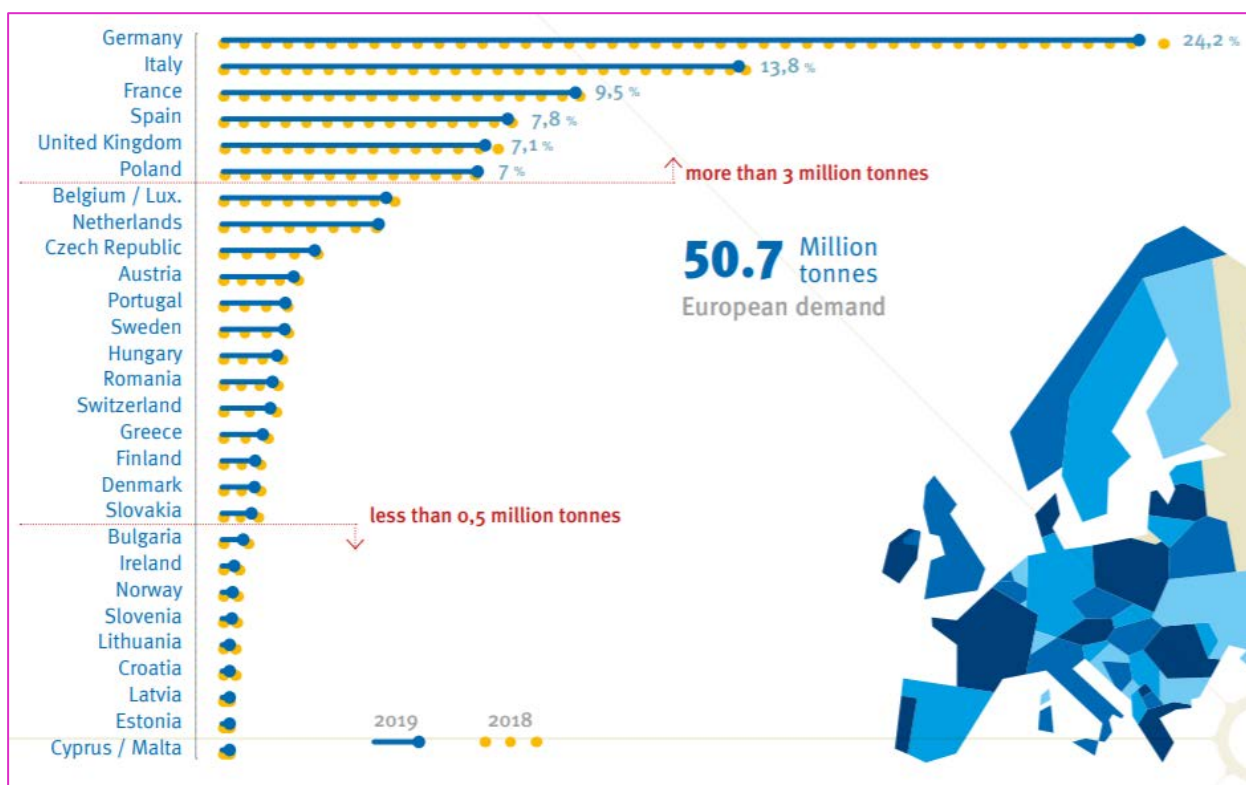


Figure 3. European plastic converter demand per country [1].

### 2.1.1 Sectorial demand

Various main market sectors of plastic in EU-28, Norway and Switzerland are shown in Figure 4. It is clear that packaging is the largest single sector for plastics, at about 39.6% (20.1 MT), followed by building & construction and automotive sectors with 20.4 and 9.6% of converters' demand, respectively.

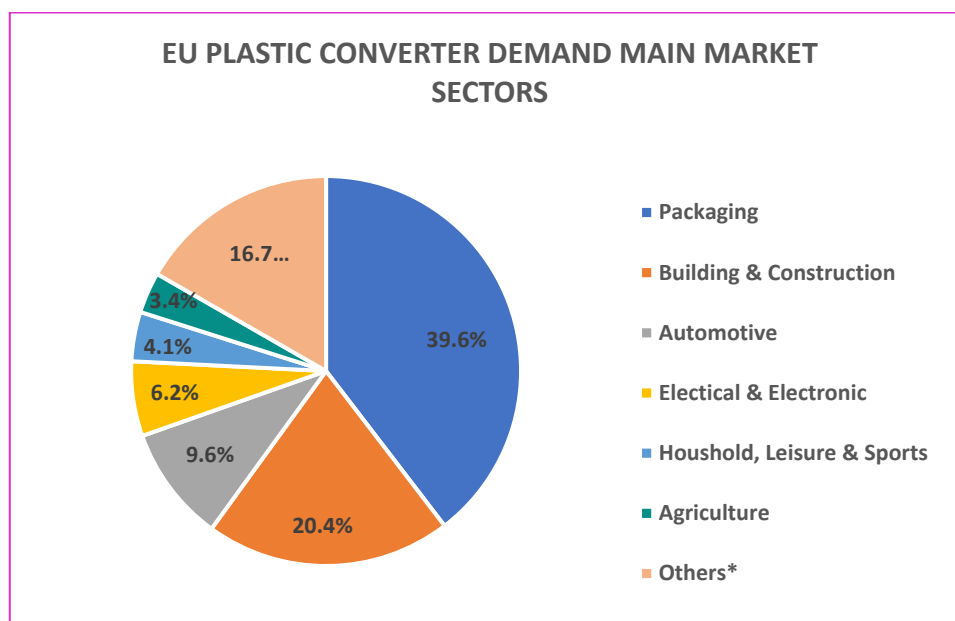


Figure 4. EU plastic converter demand main market sectors [1].

\*Others: medical equipment, plastic furniture and furniture equipment, technical parts used for mechanical engineering or machine-building, etc.

### 2.1.2 Polymer types

Figure 5 represents plastic conversion industry demand by type of plastic in EU-28, Norway and Switzerland in 2019. PE accounts for 29.8%, including LDPE, LLDPE, MDPE and HDPE. The share of PET is low in Europe (7.9%) compared with the world level.

The demand of the EU plastic converters by segments and polymer type has been shown in Figure 6. Automotive and building & construction are the main end-use markets for PA and PU resins, respectively.

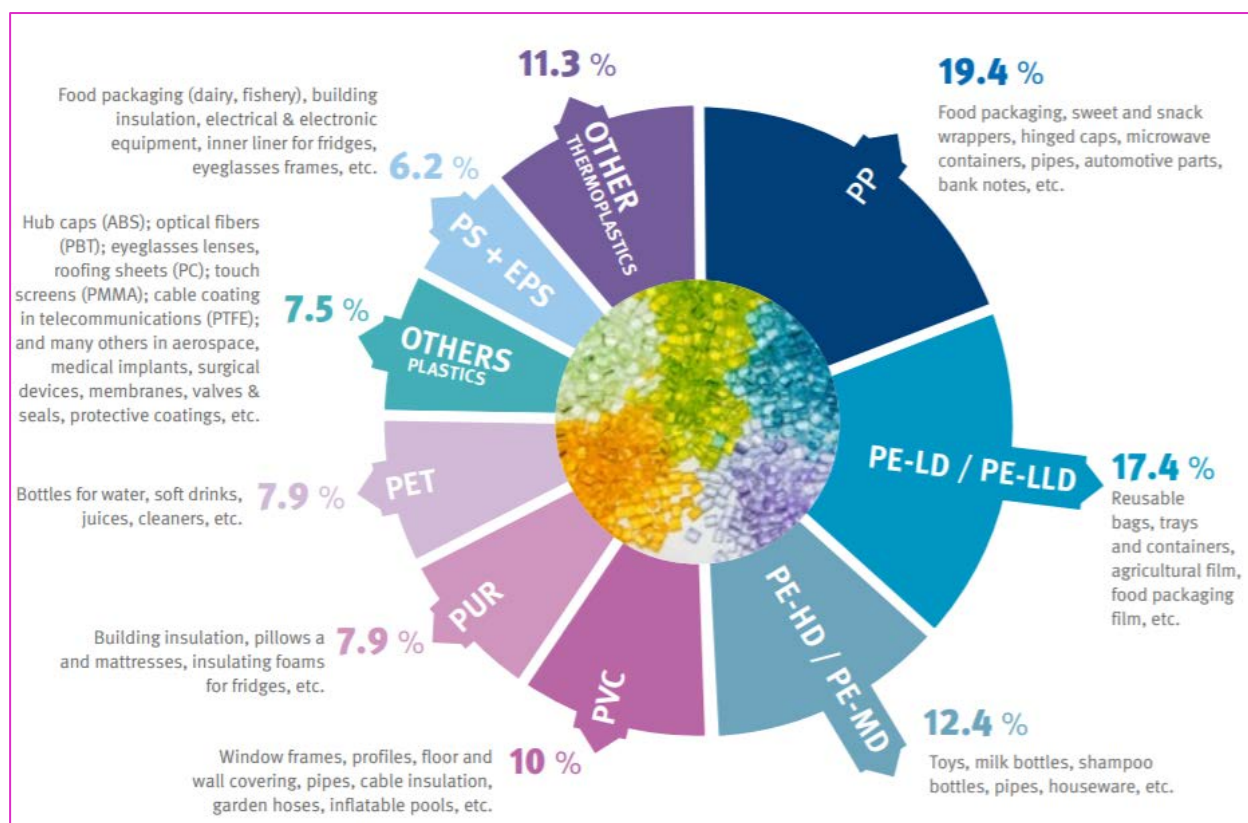


Figure 5. EU plastic converter demand by polymer types in 2019 [1].

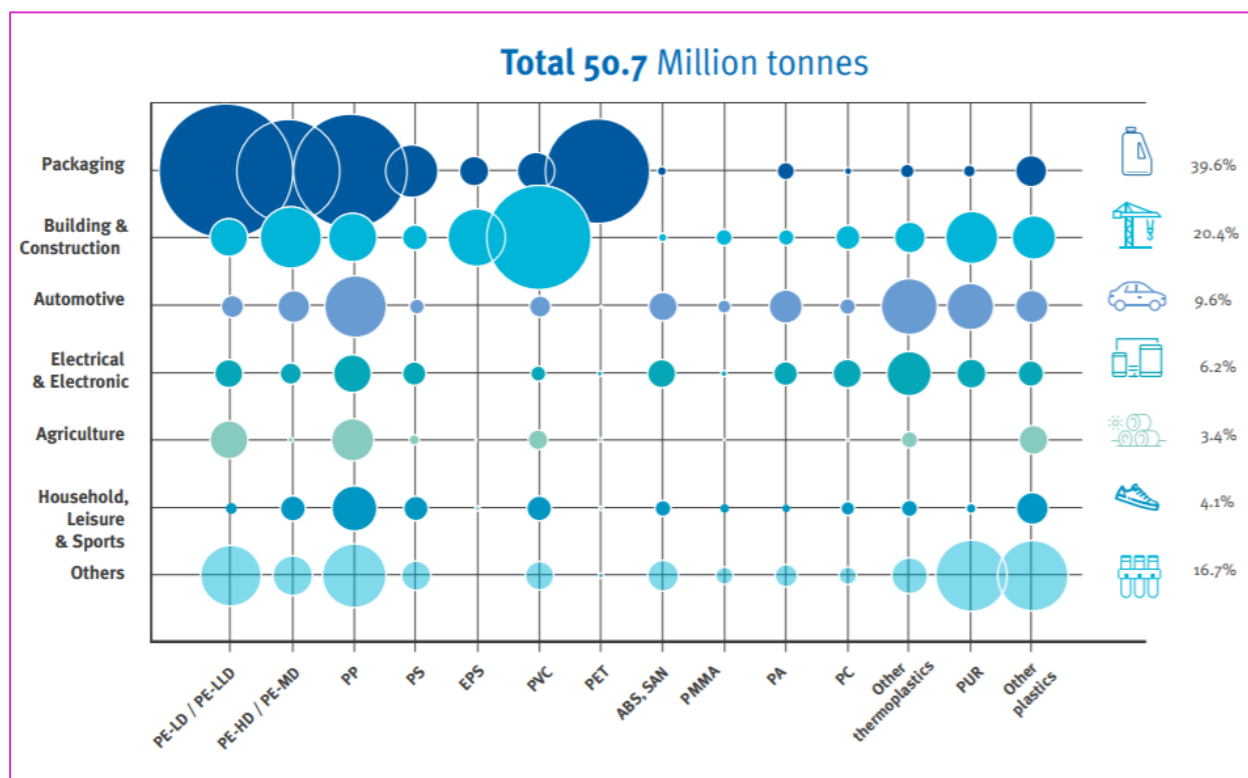
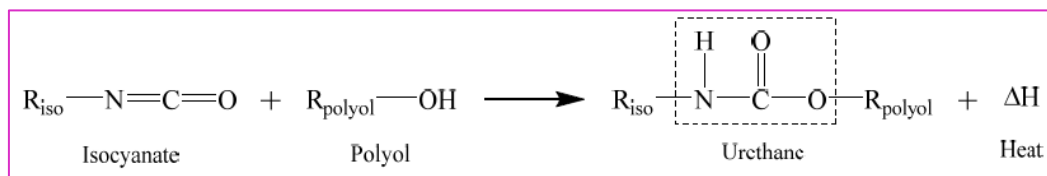


Figure 6. European plastic converter demand by segments and polymer types in 2019 [1].



## 2.2 POLYURETHANE AND ITS MAIN MARKET SECTORS

Polyurethanes are polymers that are formed by the reaction between OH (hydroxyl) groups of a polyol with the NCO (isocyanate functional group) groups of an isocyanate, and the name is associated with the resulting urethane linkage [2]. This reaction is exothermic, and leads to the production of urethane groups as described before and illustrated in Scheme 1 [3].



Scheme 1

Where  $R_{iso}$  is derived from the isocyanate monomer, while  $R_{polyol}$  is derived from the polyol component.

PUs are versatile material which can convert in various forms such as thermosets, thermoplastics and synthetic rubber (elastomers).

Today, PUs are used as everyday life products, being one of the most important class of polymers that keep changing the quality of the human life. The worldwide consumption of PU was estimated at 60.5 billion USD in 2017, and it was predicted to be over 79 billion USD by 2021 [4]. In 2016, it represented nearly 9% of the global consumption of plastics which place them as the 6th most used polymer in the world [1,5].

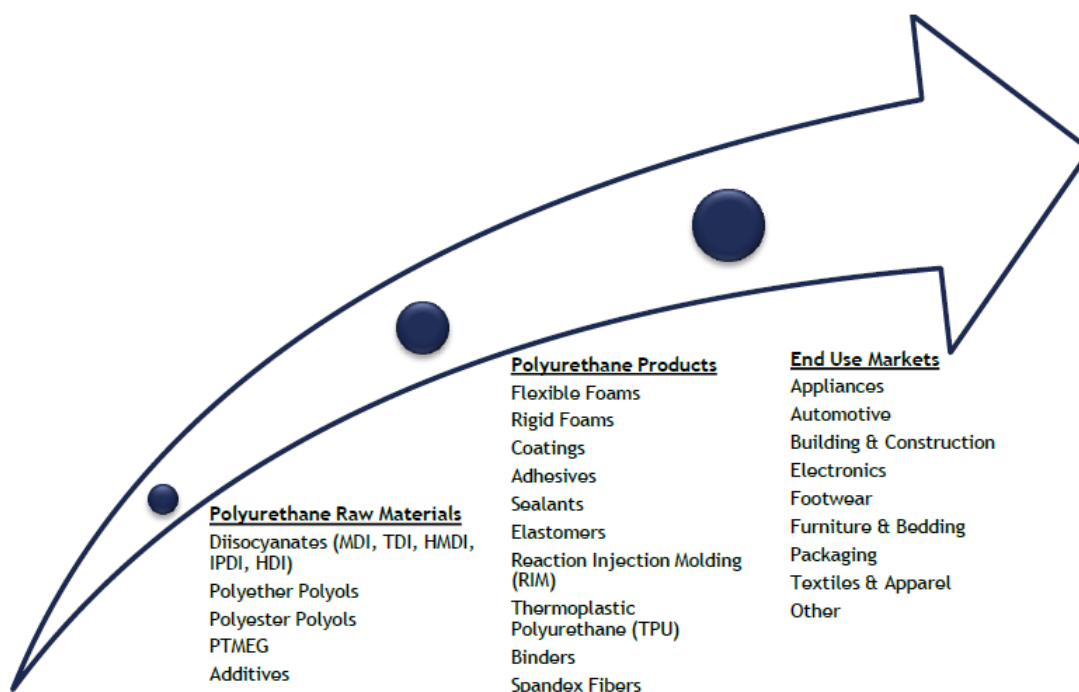


Figure 7. PU value chain [6].

Furthermore, total production of polyurethane products is reported to have been 6.52 MTs in 2019 which shows a slightly increase compared to 6.47 MTs in 2017 and to 6.16 MTs in 2015. However, it is expected



to face with lower production volumes by 15.8% in 2020 due to the Covid-19 pandemic, and it is not anticipated to surpass the 2019 production volume again until 2024.

The COVID-19 consequences are likely to cause a much more dramatic fall in production of polyurethane products in 2020, with some end-use industries like automotive sector suffering more than others.

By 2024, this figure is forecast to be 6.62 tonnes, equivalent to an average growth of 0.3% p.a. over the next five years. Polyurethane production mostly takes place in Western Europe (Figure 8), and the region's total PU output exceeded 3.65 million tonnes in 2019, with some 965,300 tonnes produced in Germany alone. However, the growth rate outside Western Europe is faster. In 2019, the PU output of Central Europe and the Middle East increased by 2.1% and 1.5%, respectively. On the contrary, Eastern Europe's production declined by 0.4% due to the poor performances of Russia and Turkey [6].

Table 1. Total EMEA Production of All PU Products & Growth Rates by Region, 2017-2022 (Tonnes) [6].

Country	2017	2019	2024	2019-2024 (% Growth p.a.)
Western Europe	3,615,237	3,647,397	3,657,125	0.1
Eastern Europe	1,767,265	1,787,715	1,847,155	0.7
Middle East & Africa	1,090,844	1,083,613	1,116,965	0.6
Total EMEA	6,473,346	6,518,425	6,518,425	0.3

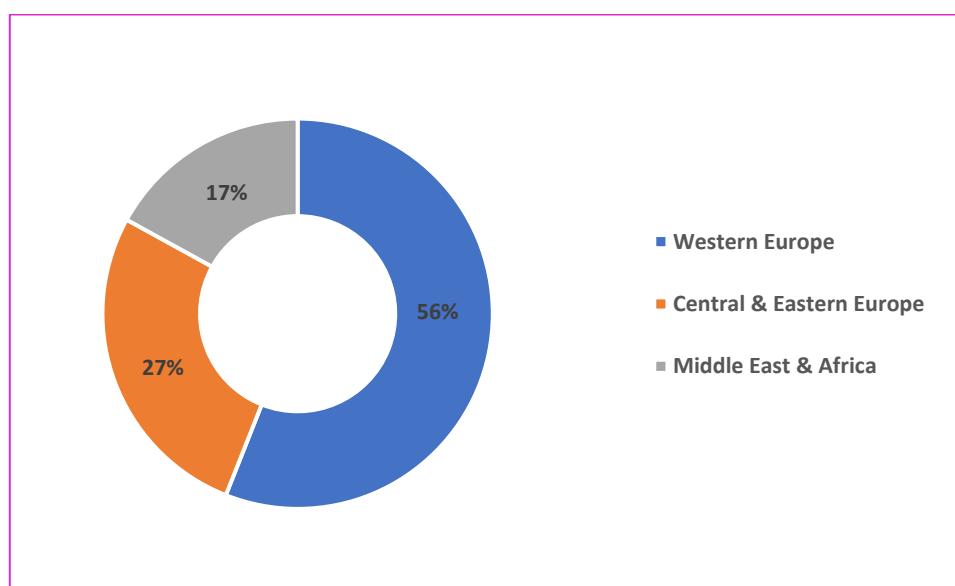


Figure 8. Production of all PU products by region in 2019 [6].

Moreover, as illustrated in Figure 9, the principal consumption of PUs is in the form of foams which correspond to 67% of global PU consumption.

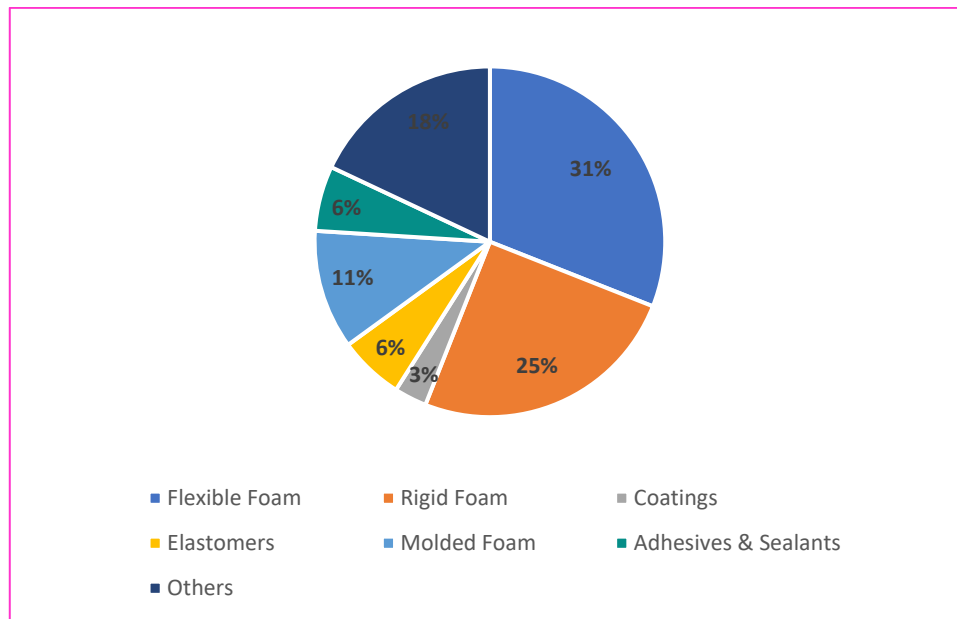


Figure 9. Global consumption of PU in 2016 [7].

The industry is anticipated to face a strong growth by the reinforcement of construction industry especially in Eastern Europe countries such as Poland, Hungary, and Slovakia. Furthermore, the EU schemes to provide financial incentives for the use of environmentally friendly products is expected to drive the market for Polyurethanes. Germany was the leading consumer of PU in Europe with demand share estimated at  $\approx 18\%$  in 2015 owing to its major automotive sector and export business of cars [8].

### 2.2.1 PU application segments

The PU market is segmented on the basis of application as foams, coatings, adhesives & sealants, elastomers, and binders.

Since the technology to produce PU foams is so well-established, this type of foams corresponds to half of the whole polymeric foam's market [9]. The main types of PUFs are the flexible foams and rigid foams; nevertheless, other classifications can be attributed to PUFs, such as flexible PU slabs, flexible moulded foams, reaction injection moulding (RIM), carpet backing, or two-component formulations, etc [9, 10].

In addition, flexible foam was also the largest product group, accounting for 34% of the total EMEA polyurethane output in 2019. It was closely followed by rigid foam at 33%. However, the detrimental consequences of COVID-19 are expected to impact flexible foam more than rigid foam, which will result in the latter having a higher share of production in 2020 and 2021. IAL forecasts that rigid foam production will decline by 12.6% in 2020, while flexible foam is projected to contract by over 20% to bring the rigid foam production volume above that of flexible foam for the first time [8].

EU regulations eyeing to the energy efficiency of households and financial incentives further drive the foams growth.

Amongst the polyurethane CASE markets, the largest product group was polyurethane coatings, accounting for 14% of the total EMEA PU production [8].

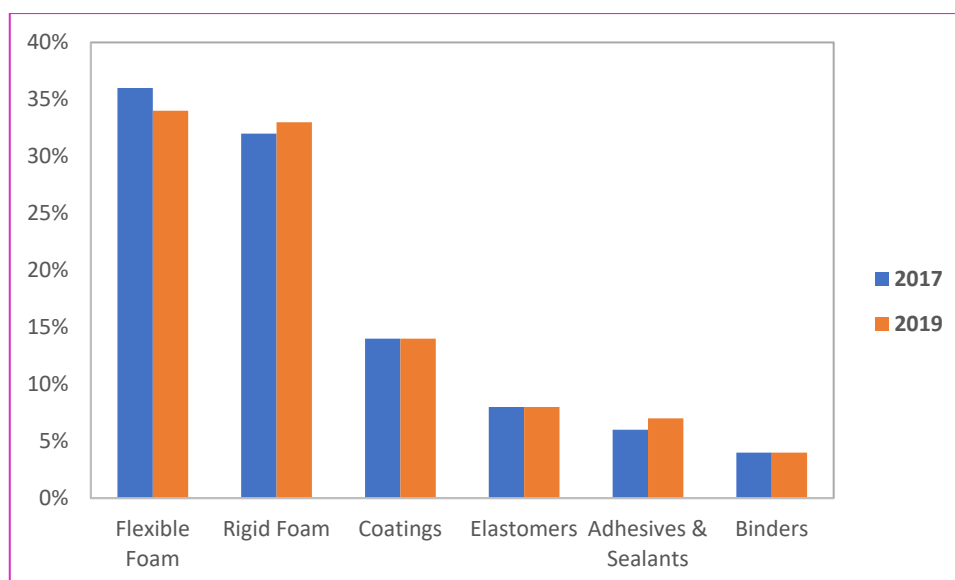


Figure 10. EMEA PU production by type [12].

Although many aromatic and aliphatic polyisocyanates exist, two are of particular industrial importance. Each of them has variants and together they form the basis of about 95% of all the polyurethanes [12]. They are:

- TDI (toluene diisocyanate or methylbenzene diisocyanate)
- MDI (methylenediphenyl diisocyanate or diphenylmethane diisocyanate).

The EMEA consumption of MDI and TDI was approximately 1.97 million tonnes and 678,500 tonnes, respectively, in 2019. This represents an annual change of 1.8% for MDI, and -0.7% for TDI, since 2017 [8].

The consumption of MDI showed stronger growth than TDI in the past five years and is expected to increase its market share further in the upcoming years. The demand for TDI remained relatively static in the past five years in EMEA. The market is expected to decline by 19% in 2020, which is mainly caused by the bad performance of end-use segments throughout the COVID-19 pandemic.

The EMEA MDI market is largely driven by the use of PU rigid foam for thermal insulation in the construction industry, whereas TDI is primarily used in flexible foam production, with mattresses, upholstery and transport seats representing the main end-use applications. There is also demand for both products in the CASE markets, but in much smaller quantities.

**Rigid and flexible polyurethanes.** Rigid PU foams represent one of the most commonly known versatile and energy saving insulation materials [13]. These foams can significantly reduce energy costs on the one hand and can make commercial and residential appliances more comfortable and efficient on the other. To ensure a stable temperature as well as a reduced noise level for both home and commercial appliances, builders often resort to using polyisocyanurate and PU foams. These foams have been proven to be

effective as insulation materials, and hence have been applied in window insulations and wall and roof insulations as well as in barrier sealants for air and doors.

The preparation of rigid PU foams can be performed using petroleum-based polyols as well as with bio-based polyols from vegetable oils or plant-based lignin. The properties of the formulated PUs depend on the category of the hydroxyl group present in the polyols.

On the other hand, flexible PU foams comprise some block copolymers whose flexibility is based on the phase separations between the soft and hard segments [14]. Thus, PU foams may be modified through deliberate control of the individual compositional ratios of these segments. Depending on some physical characteristics they may be classified as flexible PUs; for example, in terms of density, durability, firmness, tearing resistivity, combustibility, surface elasticity, etc., where a combination of these properties can ensure a good flexibility in the PU compound. Flexible PU foams find application as cushion materials for a wide range of consumer and commercial products, including carpet underlays, furniture, bedding, automotive interior parts, packaging, biomedicine and nanocomposites [15-18].

Rigid and flexible PU foams are also defined depending on whether the cell structure is 'open' or 'closed'. In rigid PU foam only a few percentages of cells are opened wall; the bulk density of these products is about 30–35 kg/m<sup>3</sup>. The blowing agent gas contained in the cells results in a very low thermal conductivity, and the main use of rigid PU foam is in insulating panels of refrigerators. Flexible PU foams have a virtually completely open cell structure with typical densities of 20–45 kg/m<sup>3</sup> and are, therefore, not useful as insulators [19].

PU rigid foam production in EMEA grew by 2.3% in 2019 to reach 2.14 million tonnes, of which the bulk is used for thermal insulation in the construction and refrigeration industries in the form of panels, boards and in-situ foam. Insulation remains one of the fastest growing areas for polyurethane in EMEA, in spite of the volatile economic climate that persists in the region. The majority of PU/PIR insulation products are taken up by the construction sector, and building energy efficiency is still the key driver for the use of rigid foam in insulation applications. The focus of the insulation market is on fire retardancy and lower lambda values and, subsequently, conventional PU systems are gradually being replaced by polyurethanes with enhanced fire resistance properties, as fire classification grades of B2 and above are increasingly in demand. This has also led to the preference for PIR panels compared to traditional PU systems [11].

Overall, the demand for rigid polyurethane is growing at faster rates than for other polyurethane products, including flexible foam. Rigid-faced sandwich panels remain the largest end-use application for rigid PU foam in the EMEA region, accounting for more than 30% of the total rigid foam production. Europe continues to lead innovation in this market segment, and the differences between Eastern and Western Europe are not as distinct as they were in the past. Polyurethane rigid foam production is still relatively limited in the Middle East and Africa. The production volume is, however, expected to grow in the upcoming years, which will mainly be due to better awareness of the need for insulation and tightening energy legislation [6].

Total production of flexible polyurethane foam in 2019 in the EMEA region was 2.21 MTs, a decrease of 0.9% compared to the previous year. Western Europe has traditionally been the hub for flexible slabstock foam production, with large-scale production of conventional polyether, HR, viscoelastic and polyester foams. Even though the quantities produced in the region remain very prominent, there has been a definite

shift of production towards the east, in particular to Poland and Romania. These two countries have experienced tremendous growth in their polyether slabstock output in the last decade, resulting in much lower growth rates in Western Europe. In response, many West European producers have focused their attention on high-end, more advanced foam as opposed to conventional PU slabstock. In general, the demand for the high-end products, including HR and viscoelastic foam, has continued to grow in the last couple of years, driven by the enhanced comfort, good performance and excellent quality they offer. The producers of flexible foam slabstock for furniture and bedding applications have been particularly affected by TDI shortages and price increases, which has limited the market growth. Indeed, moulded foam for the automotive industry, including applications such as car seats and NVH foam, has outperformed furniture production in EMEA and has provided the main impetus for flexible foam. Passenger car production in the EMEA region reached 22 million units in 2017, an increase of 3.9% over 2016 and also 4.2% over 2015 [11].

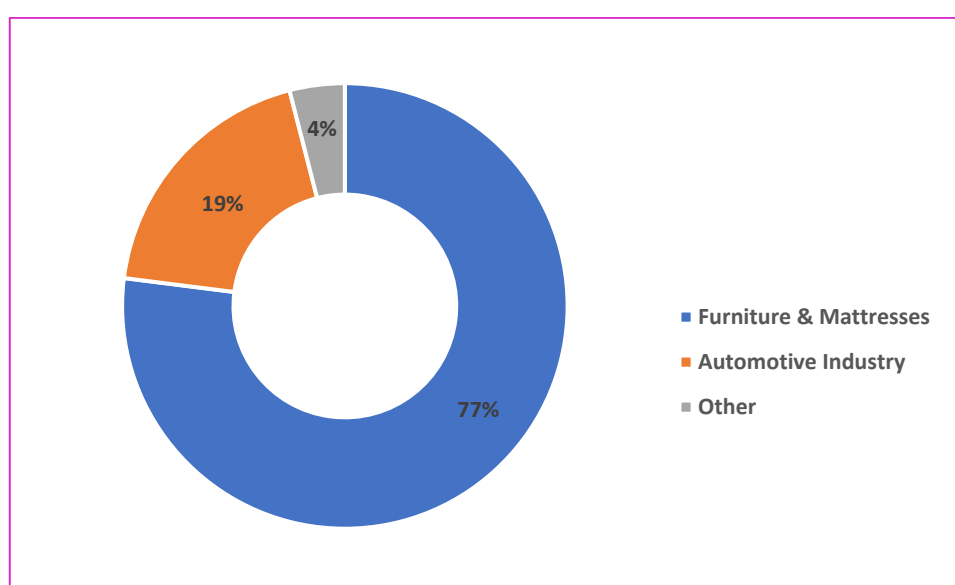


Figure 11. Application segments of flexible polyurethane foams in Europe [20].

**Coatings, Adhesives, Sealants and Elastomers (CASE) applications.** There is a growing range of applications and advantageous markets that may be derived from the use of PUs as CASE. This is because PUs often reveal excellent and versatile mechanical, chemical and physical properties [21-22]. PU adhesives can offer good bonding properties, whereas very tight seals may be obtained from PU sealants. For a PU to be suitable for coating applications, it needs to possess good adhesive properties, high chemical resistivity, excellent drying, low temperature flexibility and adequate scratch resistivity [23-24]. Sometimes, to impart anticorrosive properties into the material, different types of nanoparticles, such as titanium oxide, silicon dioxide, may be used for high-performance coating applications.

It is noteworthy that despite the suitability of PU coatings to offer certain desirable properties, their impact resistance insufficiency and susceptibility to UV degradation when used for outdoor purposes can reduce their use [25-27]. Consequently, improvements in these shortcomings using several synthetic methods for producing PU coatings with enhanced properties have been reported in the literature [28].

PU elastomers are another type of important materials, which may be used for a variety of useful application, such as shoe soles, household items, surfboards, goggles and ski boots. They may be fashioned

into a wide variety of shapes, colours and design. They are lighter compared to metals, and can provide highly desirable stress recovery properties as well as can withstand several environmental factors [29,30]. Although they have an elastic property, they also possess some degree of plastic nature. Thus, in practice, the highly desired elastic property cannot be maximally obtained. In a bid to overcome this challenge, the incorporation of graphene oxide into the PU formulation was investigated [31]. Also, hybrid fillers, such as titanium oxide or carbon nanotubes, are added to serve specific purposes. In most cases, PU-elastomer-based nanocomposites are prepared via the common solution cast method. From the literature, it was found that the elastomeric properties of PUs were exploited to produce graphene-oxide based dielectric materials [32]. The suitability of the material for this application is based on the ease of their actuation in an electric field. Thus, this kind of materials are very useful for their tolerance to high physical strains, such as during shrinkage and expansion during the application of electric voltage.

Total EMEA production of polyurethane coatings was nearly 924,000 tonnes in 2019, which showed a slightly increase in comparison to 2017. The market is, however, expected to contract by 16.2% in 2020 and will reach the market size of 2019 by the year 2023 again. The main reason behind this sharp decline is the impact of COVID-19 on the automotive industry. The main utilisation areas for PU coatings traditionally include transport, construction, and wood and furniture coatings. The coatings segment remains one of the most stable of all polyurethane product categories; markets such as automotive refinish, corrosion protection and construction have an enduring need for PU-based coatings. The demand for water-based PU dispersions is increasing faster than solvent-based coatings. The EMEA market for adhesives and sealants has gone through a period of steady growth in the last few years, reaching over 436,000 tonnes in 2019, whereas it was around 418,500 tonnes in 2017. Polyurethane adhesives are available for a diverse range of applications, with most production currently taking place in Western Europe, in particular in Germany, where most leading manufacturers are located. The demand for PU adhesives tends to follow general economic developments; however, above GDP growth is forecast for applications such as flexible packaging and construction in Europe. In addition, excellent growth opportunities exist in the Middle East and Africa, where the demand for PU adhesive and sealants is currently very limited. Their extremely high performance enables the use of synthetic polyurethane elastomers in a range of different sectors such as automotive, construction, mining, aerospace, electronics, medical devices, sports products and fibres. Most demand comes from the automotive and footwear industries. Total EMEA production of elastomers was some 550,000 tonnes in 2019. Even though most PU elastomers are still manufactured in Western Europe, the fastest growth rates are present in the Eastern part of the continent. In particular the production in Turkey is forecast to increase in the next five years, thanks to the ongoing investment in PU elastomer production in the country [6].

COVID-19 is expected to be more detrimental to elastomers than adhesives and sealants, but less so than to coatings, and IAL forecasts a 14.7% decline in production in 2020 [8].

**Binders.** PU binders are often used to bond different types of fibers and other materials to each other. Binders made from PU help to provide a permanent gluing effect between organic materials and long-strand lumbers, oriented strand boards, laminated veneer lumber, medium density fiber boards, particle boards and straw boards. As a binding material, the ratio of the hard-/soft segments of PUs should be high and good thermal stability is required. Sometime a specific or moderate acid number (not too high or not too low), weak crystallinity, limited molecular weight and narrow particle distribution (if PU dispersion) are preferred for a good quality binder. To impart excellent chemical resistivity in PU binders, hybridization

with acrylic polymer is also preferable. The main areas of application are in elastomeric or rubbery flooring surfaces, wood panel manufacturing, ink-jet printing, foundry industries and sand casting [33-34]. Among these, the major application to which PU binders are put is in the production of oriented strand board (OSB). The use of these panels cut across flooring and structural sheathing, shop panels, joist and beams and other manufactured housing applications. Also, the fabrication of rebonded foams, which are used as carpet underlay, mainly take advantage of PU binders and other chemicals to adhere flexible scrap PU foams to the underlay carpeting. Due to its excellent binding properties, PU has been proposed as a suitable alternative to binders based on organic solvents [35-36].

Binders represent a comparatively small segment of the overall PU market, with the total EMEA output of 250,000 tonnes in 2019, slightly higher than its volume in 2017 (240,000 tonnes). The vast majority of this was destined for the manufacture of wood composite panels, and in particular OBS boards. The production of these panels is stagnant in Western Europe, but the market is experiencing dynamic growth in Eastern Europe. The fallout of COVID-19 is anticipated to cause a contraction in production of 10.8% in 2020, with the market fully recovering by 2023 [6, 8].

### 2.2.2 PU end-user market segments

**Building and construction.** Nowadays buildings need to meet certain requirements in terms of the use of construction materials, including high performance strong materials, light weight, easy to install, durable and versatile. These may be achieved through the incorporation of PUs into building and construction materials.

In fact, the use of PUs could offer great conservation of natural resources and help the environment through reduced energy consumption. The use of PUs for construction and building applications is on the increase due to their specific properties, such as excellent heat insulation capacity, highly desirable strength-to-weight ratio, versatility and durability. An experimental work was performed to determine the reduction of heat loss through a building envelope for the case of thermoregulating microcapsules contained in PU foam [37].

Analysis showed that with an incorporation of 40% microcapsules it was possible to produce a thermoregulating foam with two possible advantages: energy accumulation and insulation during the transient state. Furthermore, the cheap cost of these high-performance materials coupled with their comfort ability have made PUs an integral part of many homes. PUs can be used in almost any part of the home, such as for floors, e.g. in the form of pads of a flexible cushion for carpets, or for roofing, e.g. in form of heat and light reflecting materials. In the roofing application, the plastic coverings on the PU surface can help to keep the house cool on the one hand, and help to reduce energy usage on the other hand. Generally, PU materials help to add flexibility to new homes, such as the entry door and garage doors, which contains panels with foam cores. The foam-core panels also provide a lot of colour variation and profiling for roofs and walls.

**Apparel.** When scientists discovered that polyurethanes could be made into fine threads, they were combined with nylon to make more lightweight, stretchable garments. Over the years, polyurethanes have been improved and developed into spandex fibers, polyurethane coatings for fabrics, and thermoplastic elastomers.

Thermoplastic polyurethane elastomers can be moulded and shaped into different parts. When these elastomers are spun into fibers they produce a flexible material called spandex, which is used to make sock tops, brassieres, support hose, swimsuits, and other athletic apparel.

Polyurethane coated fabrics are durable and abrasion-resistant, yet soft, light and breathable. As such, they are used to create more comfortable and sophisticated weatherproof clothing such as sports anoraks and light rain clothes. Polyurethane coatings are also used for leather-like materials, such as imitation suede and as man-made leather for garments that not only look like leather, but also have similar stretch, stiffness and permeability properties [38].

Because of today's advances in polyurethane techniques, manufacturers can make a broad range of polyurethane apparel from man-made skins and leathers used for garments to sports clothes and a variety of accessories.

**Automotive.** The areas of PU application in the automotive industry are vast. Aside from its common use as a foam to make vehicle seats more comfortable, it may also be used in car bodies, bumpers, doors, windows and ceiling sections. PUs also help to provide better automobile mileage through reduced weight, increased fuel economy, good insulation with proper sound absorption [39], great comfort for passengers [40] and high corrosion resistance properties. Deng R. and his colleague opined that since a clear majority of vehicular seats are mainly foams, the dynamic comfort of users may be controlled by modifying the foam properties to obtain the desired quasi-static features [40]. Due to the low density of PU foams, they are suitable for the manufacture of stiff and light components, which may then be used as interior panels in aircrafts, structural shapes, such as bulkhead cores, stringers and transform cores in reinforced plastic boats, etc. Several other sandwich materials found in high-end sporting cars, ships, aircrafts and racing cars are also based on PU. This is because the PU material can help to provide heat shielding and structural stiffness as well as crash energy management. PU adhesives are also used as PU–aluminium laminates for automotive applications. These adhesives are prepared from polycaprolactone polyols and a mixture of aromatic and cycloaliphatic diisocyanates. The adhesion property has been found to be influenced by the structure of the PU used.

Coatings are another prime need for automobiles and can also be prepared by using PU. The development of modern technology related to nanofillers or nanoparticles can add some important features in PU-based advanced coating materials for automobiles.

**Marine applications.** PU materials have contributed a large innovation to the recent development in boat technology. PU-based epoxy resins help to protect boat hulls from weather, corrosion and water as well as other substances that may increase drag. In addition, PU-based rigid foam helps to insulate boats from extreme temperatures and noise. It helps to provide increased tear and abrasion resistance, and offers good load-bearing properties even at minimum weight. Based on these, the maritime industries often incorporate several thermoplastic PUs into various products for the specific advantages they provide, including elasticity, durability and ease of processing ability with good suitability for cable and wire coatings, drive belts, hydraulic seals and hoses and engine tubing as well as ship construction.

Some PUs can also be used to recognize certain active materials [42], and for removing certain organic substances from water bodies. For marine applications, accelerated weathering or ageing analyses of the



materials are very important. A study concluded that the PU material could help retain the mechanical integrity of products even under adverse environmental conditions [43].

**Composite woods.** Polyurethanes play a major role in today's modern materials such as in composite wood, which is a combination of synthetic and natural materials. Polyurethane-based binders, typically used both with wood and rubber, are used in composite wood products to permanently glue organic materials into oriented strand board, medium-density fibreboard, long strand lumber, and even strawboard and particleboard.

**Coating applications.** Over the years, there has been continuous research on suitable materials for coating applications. PUs have been reported to possess great potential as paint and surface-coating materials [44-45]. Research in this area saw the development of certain non-linear hyperbranched polymers, which have metamorphosed into other hyperbranched PUs with gloss, high solubility and flexible coating properties [46]. To modify these hyperbranched materials for certain flame-retardant coating applications, compounds containing nitrogen, halogen or phosphorus may be incorporated into them [45]. Another type of coating material suitable as a marine antifouling material was produced from polyester-based polyol. Pentaerythritol and trimethylolpropane were used as initiators and polycondensation was done with 3-caprolactone, using the cross-linker hexamethylene diisocyanate trimer. The synthesized antifouling coating material was also found to be highly degradable [47].

**Medical applications.** Polyurethanes are commonly used in a number of medical applications including catheter and general-purpose tubing, hospital bedding, surgical drapes, wound dressings, as well as in a variety of injection moulded devices. Their most common use is in short-term implants.

Today's polyurethanes have been formulated to provide good biocompatibility [48], flexural endurance, high strength, high abrasion resistance and processing versatility over a wide range of applications. These attributes are important in supporting new applications continually being found by medical device manufacturers including artificial hearts, catheter tubing, feeding tubes, surgical drains, intra-aortic balloon pumps, dialysis devices, non-allergenic gloves, medical garments, hospital bedding, wound dressings and more.

Polyurethanes can outperform many other materials in flexibility, tear resistance and abrasion resistance. This is because many devices that are used in these areas can rub against other materials and bend repeatedly. Without polyurethanes, the continued rubbing and bending could result in the device weakening or could cause failure in extreme cases.

TPU's, also known as polyurethane elastomers, have molecular structures similar to that of human proteins. Protein absorption, which is the beginning of the blood coagulation cascade, was found to be slower or less than other materials. This makes them ideal candidates for a variety of medical applications requiring adhesive strength and unique biomimetic and antithrombotic properties. For example, TPU's are currently being used as a special sealant to bind bundles of hollow fibers in artificial dialysis cylinders.

With the advent of new surgical implants, biomedical polyurethanes can lead the way to eliminate some acute and chronic health challenges. Polyurethanes are popularly used in cardiovascular and other biomedical fields due to their good biocompatibility as well as their mechanical properties. Many of these polyurethanes have elastomeric properties that are accompanied by toughness, tear resistance and

abrasion resistance. They have been widely used in applications such as the artificial heart and pacemaker lead insulation, among others.

Patients using polyurethane medical devices may prefer them to other materials due to their comfort. They can be used in many soft elastomeric medical applications such as indwelling catheters and vascular access. Soft polyurethanes can be more comfortable yet stronger than other soft materials, which makes them a unique material for this application [49].

Polyurethanes made significant contributions to the medical industry. By virtue of their range of properties, they will continue to play an important role in the future of science and medicine.

**Appliances, flooring and packaging applications.** Most of the appliances that consumers use these days are based on PUs. Rigid PU foams lead the way in the number of applications as they can be used as thermal insulators for refrigerators and freezers. These materials have become so essential due to their cost effectiveness, which make them suitable for use to meet the required energy ratings in most freezers and refrigerators.

The advantages that rigid PU foams provide to these appliances are due to the combination of cell gases and fine foams with a closed-cell structure, which helps to prevent heat transfer.

For flooring purposes, PUs have several specific applications, such as top coatings or as carpet underlay foams. They can help to make floors more durable, aesthetically pleasing and easy to maintain. The lifespan of carpets and their appearance can be increased through the use of PU foam underlays, which can also help to provide better comfort with reduced ambient noise. PU-based protective finishes can also be used as floor coatings, where they can provide solvent and abrasion resistance on the one hand and ease of cleaning and maintenance on the other hand. Except for those properties, the lifetime or service period is also equally important to consider. In one study, the time–temperature–stress dependent shear creep behaviour of PU foam was analysed and Findley's power law, extended to include Arrhenius equations, was used to propose a model for the temperature dependency on the viscoelastic parameters [50].

Combining all the properties, PU finishes can offer a better look to new wood, cement or parquet floors, and can also offer a regenerated appearance to older floors.

For packaging applications, PU can also be used as a printing ink or as packaging foams. A PU plasticizer was prepared from palm olein and castor oil for packaging applications [51]. This PU plasticizing resin showed high flexibility with good mechanical and freeze resistivity. On the other hand, PU packaging foams offer a wide range of packaging options, which should help to overcome most onsite packaging challenges. The versatility of these foams has also been explored for the cost-effective packaging of items that demand special protection during transit, including medical equipment, electronics, large machine parts and delicate glassware. Custom-fit packaging materials have also been made available to almost all shipments using PUs.

**Electronics.** Often referred to as “potting compounds,” non-foam polyurethanes are frequently used in the electrical and electronics industries to encapsulate, seal and insulate fragile, pressure sensitive microelectronic components, underwater cables and printed circuit boards. Polyurethane potting compounds are specially formulated by developers to meet a diverse range of physical, thermal and

electrical properties. They protect electronics by providing excellent dielectric and adhesive properties, as well as exceptional solvent, water and temperature resistance. Typically, potting compounds are one or two component mixtures, solvent-free, 100% solids and are processed with simple dispensing equipment.

### 2.2.3 EU polyurethane economy

According to ISOPA [52], in Europe, there are about 200 companies directly involved in the production of polyurethane, for about 4,600 companies who are their direct customers, and more than 18,300 producers of polyurethane-based finished goods. Germany is the leading market for PU in Europe accounting for ≈18% of the market owing to its mature automotive industry. The highest number of companies involved as direct customers of polyurethane and producers of polyurethane-based products are found in Germany (850 and 3,400 respectively) and Italy (650 and 2,600). In terms of overall impact on national economies, the highest number of companies impacted are also found in those two countries, with around 44,000 companies impacted in Germany, and around 33,000 in Italy. Overall, 216,000 non-polyurethane companies are impacted throughout Europe which are mostly SMEs.

This makes for a major economic contribution to European national economies, particularly in Germany and Italy where €41,4 billion and €26,8 billion economic value are added yearly to national GNPs. In France, Poland and the UK, the economic contribution of the sector is around €18 – €19 billion, for an overall European economic value of €207,3 billion.

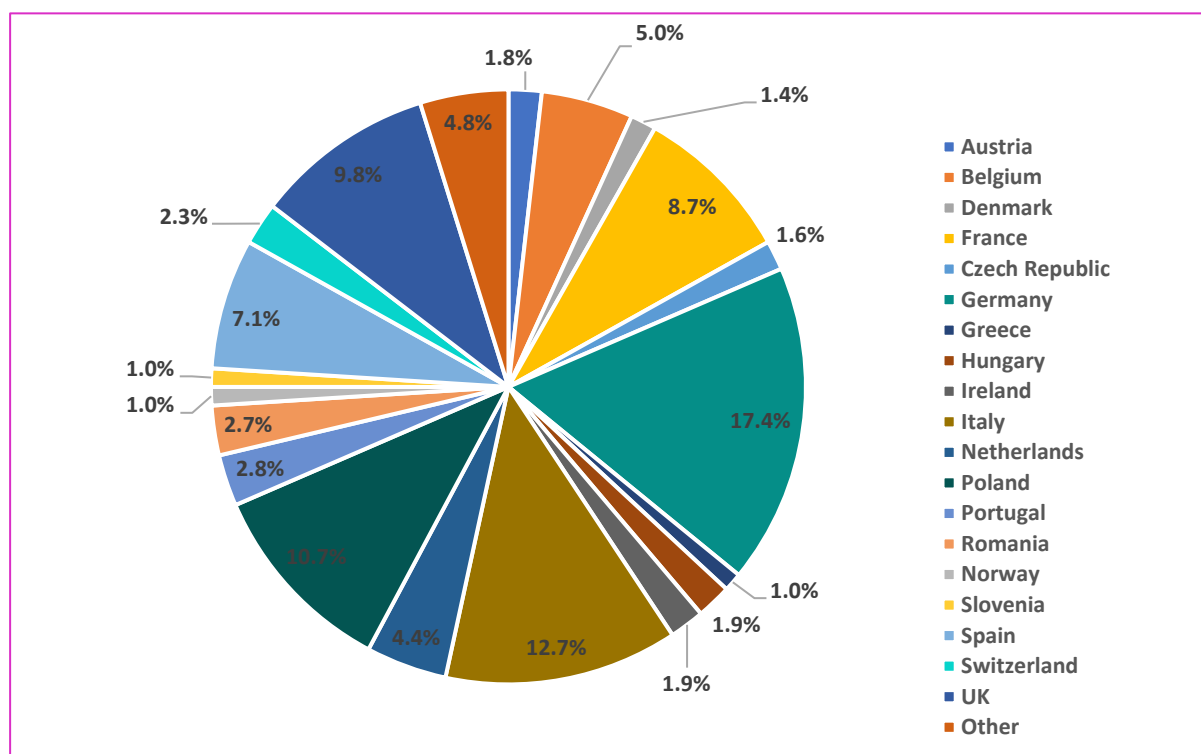


Figure 12. Total market volume per country (EU 28, Norway and Switzerland) [52].

Furthermore, increasing demand from the furniture industry and rising interest for bio-polyurethanes will offer numerous opportunities for the Polyurethanes market growth in Europe. Some of the major

companies in the region, dominating this market for its products, services and continuous product development are [8]:

- BASF SE
- Covestro
- The Dow Chemical Co.
- DuPont
- Huntsman Corp

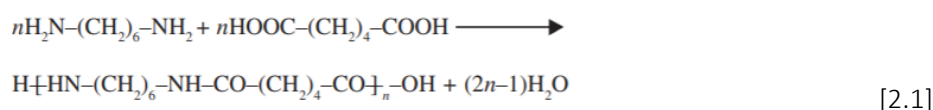
## 2.3 POLYAMIDE AND ITS MAIN MARKET SECTORS

Polyamides (PAs) are very important polymers with applications in many fields. Their outstanding properties in terms of mechanical strength, flexibility, toughness and resistance make these polymers especially interesting for diverse and special components for automotive and aircrafts, fibers, appliances and engineering components as well as in the medical sector. In addition to the petroleum-based PAs, many biobased polyamides have recently been developed with significant structures and properties. Examples are PAs based on sebacic acid, carbohydrates or on terpenes. This makes a wide variety of different polyamides accessible with a vast diversity of structures.

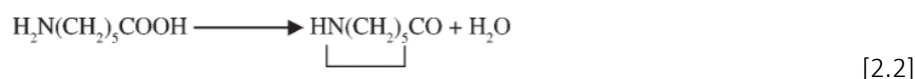
Polyamides can be formed in many ways. The four most important for industrial polymers are [53]:

1. the condensation of diamines with diacids;
2. the self-condensation of amino acids;
3. the hydrolytic polymerisation of lactams, which involves partial hydrolysis of the lactam to an amino acid; and
4. the anhydrous addition polymerisation of lactams.

Methods 1 and 3 are of major importance in the manufacture of polyamides; method 2 is used for certain speciality polyamides; and method 4 is used for reaction moulding, but not for fibre manufacture. The process developed by Carothers involved method 1, the condensation of two difunctional monomers, an amine and a carboxylic acid. Polyamides derived from diacids and diamines are generally referred to as the AABB type. They are identified as polyamide x,y, where x and y are the numbers of carbon atoms in the diamine and the diacid respectively. Although this route can form potentially many different polymers, the one that is of major commercial importance is PA66. The alternative process involves the condensation of an  $\omega$ -amino acid with the amine and the carboxylic acid groups on opposite ends of the molecule. PAs derived from amino acids are termed the AB type. They are identified as polyamide x where x is the number of carbon atoms in the monomer. PA6 is the member of this group which is of greatest commercial importance. PA66 is produced from the polycondensation of 1,6-diaminohexane, the traditional name of which is hexamethylenediamine, and hexandioic acid, which is often called adipic acid. The formation of nylon 6,6 may be represented by eq. 2.1. [54]



In the case of PA6, the normal monomer is caprolactam, which is formed when 6-aminohexanoic acid ( $\epsilon$ -amino-caproic acid) loses water internally to form a lactam, as represented in eq. 2.2:

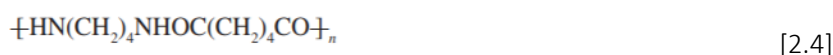


Caprolactam does not polymerise readily when it is dry. It may be converted to PA6 under anhydrous conditions by an anionic polymerisation using alkali or alkaline earth hydroxides, hydrides or alcoholates as catalysts. However, a hydrolytic polymerisation is normally used for fibres. A small quantity of water, aminocaproic acid or another monobasic carboxylic acid needs to be added to catalyse the reaction. An addition of 5–10 % of water is often used in industry [54].

Some other polyamides have been used commercially. PA 11 of the AB type is produced on a small scale as fibres but it is still widely used as a plastic. The formula of the repeat unit is given in eq. 2.3:



PA46 is polymerised from 1,4-diaminobutane and adipic acid. It was first produced on a pilot plant scale in 1984 and marketed in 1989. The polymer has a higher melting temperature, 295 °C, than PA66 or PA6. While this makes extrusion more difficult, the yarn has benefits, especially at elevated temperatures in terms of dimensional stability, heat capacity, creep and shrinkage behaviour. It is used for V- and timing belts, tyre cord, hoses and abrasion-resistant fabrics. The formula of the repeat unit is given in eq. 2.4:



Two other polyamides are used commercially to a small extent, PA610 and PA612. The former is produced for press felts for paper-making and is also used with polyamide 66 in self-crimping bicomponent fibers. Polyamide 612 is produced as a monofilament under the brand name Tynex (DuPont, USA), for use in floor care, paint, tooth and cosmetic brushes. The reduced proportion of amide groups gives lower moisture absorption as well as enhanced chemical resistance [53]. In general, specialty polyamides are more expensive and show superior performance properties for high niche applications with regard to the commodity PAs (PA6 and PA66).

The main types of polyamide polymers with their starting monomers are listed in Table 2:

Table 2. Classification of polyamides [55]

Polyamide Type	Monomers	Melting point (°C)
Polyamide 6	Caprolactam	215~225
Polyamide 66	HMDA*, adipic acid	255~260
Polyamide 610	HMDA*, Sebacic acid	213~215
Polyamide 46	Butanediamine, Adipic acid	278~290
Polyamide 11	Aminoundecanonic acid	187
Polyamide 12	Lauro lactam	176~183
Polyamide 6/6T	HMDA*, Adipic acid, Terephthalic acid	310
Polyamide 6/6IT	HMDA*, Adipic acid, Isophthalic acid, Terephthalic acid	310
Polyamide 6-MT	HMDA*, Methylpentane diamine, Terephthalic acid	305
Polyamide 9-T	Nonadamine, Methyloctane diamine, Terephthalic acid	263~306

\*HMDA: Hexamethylenediamine

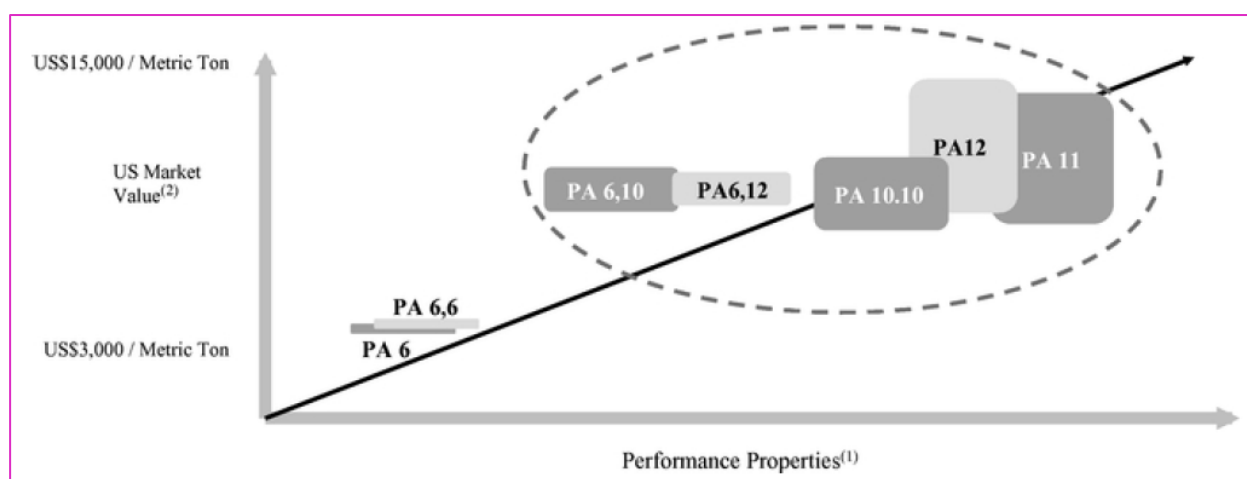


Figure 13. Price vs Performance Comparison for polyamides [56].

(1) As representative mix of properties such as: flexibility, moisture resistance, stress cracking resistance and polar fluid resistance.  
(2) Price is very dependent on end use application and volume.

In the past, the bulk of polyamide materials have been used in the form of fibers, but their use in engineering and other applications has increased to about 50%; it is anticipated that less than 50% of the polyamides produced will be used in fibers and textiles by 2020 (see Table 3).

Table 3. Polyamide Market Size by Application, 2013-2020 (kt) [57b].

Application	2013	2014	2015	2020 (Predicted)
Fibers and textiles	3888.2 (52%)	3967.2 (51.5%)	4058.3 (50.5%)	4527.6 (46.5%)
Automotive	1283.2 (17%)	1346.5 (17.5%)	1431.0 (18%)	1951.3 (20%)
Electrical and electronics	842.5 (11%)	880.8 (11.5%)	921.3 (11.5%)	1181.5 (12%)
Film and coating	496.9 (7%)	521.9 (7%)	549.6 (7%)	716.1 (7%)
Industrial/machinery	411.7 (5.5%)	427.3 (5.5%)	444.6 (5.5%)	550.5 (6%)
Consumer goods and appliances	364.1 (5%)	383.7 (5%)	405.2 (5%)	541.4 (5.5%)
Others	176.2 (2.5%)	187.0 (2%)	199.3 (2.5%)	281.0 (3%)
Total	7462.8	7714.2	8009.2	9749.4

However, according to ICIS analysis, polyamide demand in Europe will fall by 22% from 2019 to 2020 as a result of the coronavirus and the weakness in the European polyamide market is expected to continue for the rest of this year [57a]. Polyamides are now very important engineering plastics [56].

### 2.3.1 Prominent polyamides

In 2016, the global PA polymer production amounted to 7.8 MTs which can be further segmented into two prominent polymers used PA6 & PA66 [58a]. Both are used on a very large scale for a variety of applications. PA6 is tough with high tensile strength and also inhibit good elasticity.

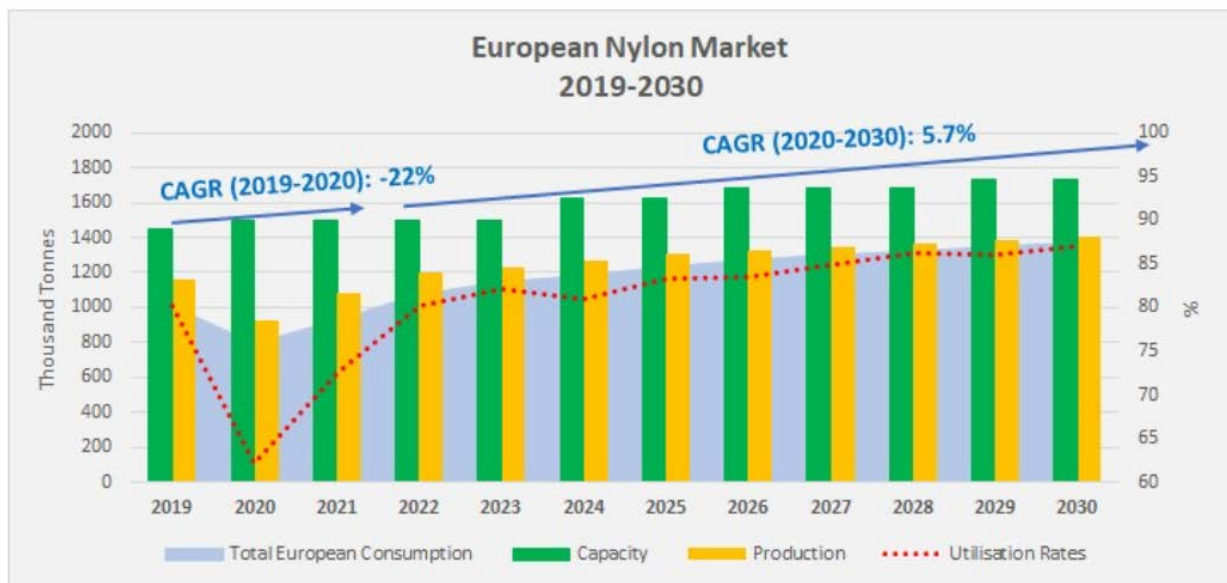


Figure 14. European Nylon Market. Source: ICIS [57a].

These type of polymer grades are wrinkleproof and resistant towards abrasion and chemicals. This makes PA6 suitable to being highly used in automotive, electrical and textile segment to produce a variety of daily use goods. Due to these suiting properties, they are highly used in sports segment (clothes, equipment, mats etc) [59].

In addition, PA66 a good surface appearance along with excellent water absorption quality. It has a high amount of modulus with better wear resistance and rigidity. They have their usage in a variety of segments to produce goods such as pipes, machine parts, zip ties, conveyor belts, hoses, 3D structural objects, apparels, airbags, carpet fibers and many others [60].

The market has witnessed tremendous amount of increase in production of these polymers in recent years. This increase in production is due to increased demand for these resins in a number of end segment markets.

Primarily the production market is driven by the excessive demand of PA6 and PA66 in the automotive and electronics sector. Increased demand for lightweight vehicles is boosting the global PA production market at a very high rate.

The global PA6 production was 4.4 MTs in 2016 and reached to 6.83 MTs in 2018 which shows a rapid increase of 7.7% CAGR from 2011 to 2018 due to China expanding PA6 capacity. The global capacity will increase to 8.86 million tons in 2024. Europe with around 1 million tons of PA6 production assigned 14.6% of global market share in 2018 [58a,b].

On the other hand, the production of PA66 was 3.4 MTs in 2016, so the production of the remaining aliphatic polyamides (mainly PA46, PA610, PA11, and PA12) is much lower. The latter group are primarily used as plastics and are usually restricted to applications where PA6 and PA66 are unsuitable. In the 1990s it was estimated that in Western Europe, plastics usage was split as follows: PA6, 48%; PA66, 40%; PA11



and PA12, 10%; and the rest, 2%. For historical reasons, usage of the various types varies from country to country [57]. For example, in the United States and the United Kingdom, PA66 was the first to be developed and remains well entrenched, while for similar reasons PA6 is more dominant in Germany. The substantial market penetration of PA11 and PA12 in France also reflects long-standing French commercial activity with these types.

The global polyamide market was valued at over 25 billion USD in 2018. Amid the COVID-19 crisis, the global market for PA estimated at 8.9 MTs in the year 2020, is projected to reach a revised size of 10.4 MTs by 2027, growing at a CAGR of 2.2% over the period 2020-2027 [61].

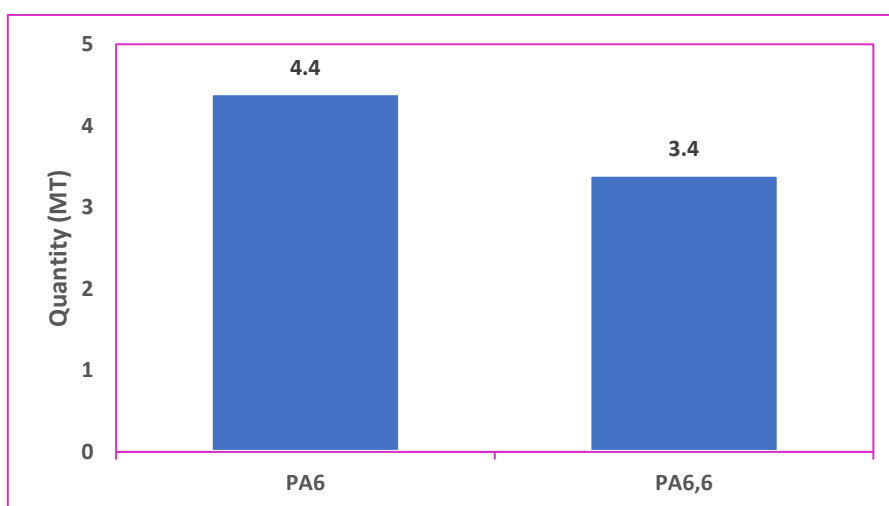


Figure 15. Global production of polyamides (PA6 & PA66) in 2016 [59].

There has also been a continuous growth in production of polyamide fibers in recent years. High-quality performance of these types of fibers makes them an ideal choice for manufacturers over their competitors (polyester). It is costlier in production than others but is still demanded for a number of applications due to its suiting properties.

Polyamide fibers are synthetic fibers and are considered to be especially tearing and abrasion resistant and have a high elasticity and shape stability. They are used for the production of a variety of products in different sectors such as carpets, ropes, sewing thread, sleeping bags, net and many others.



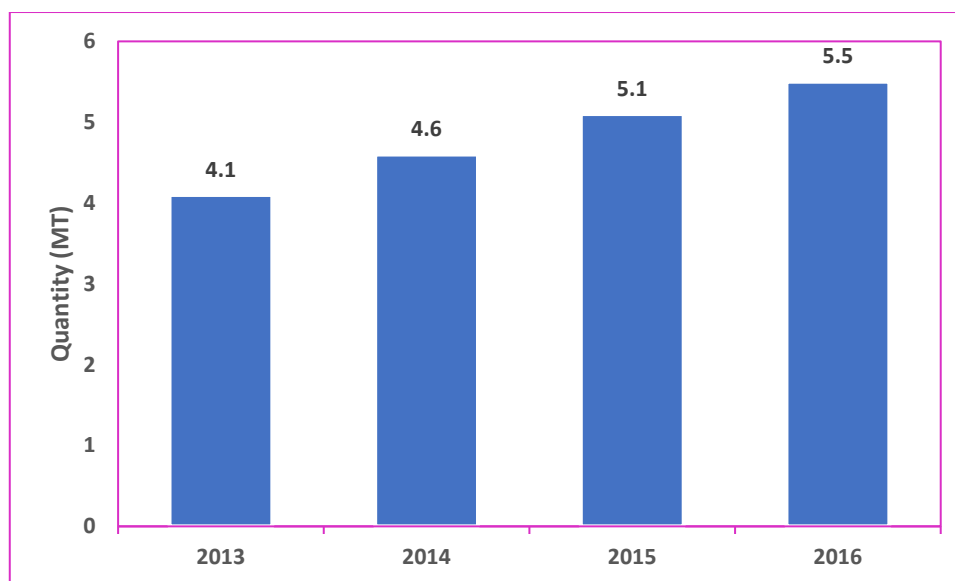


Figure 16. Global production of PA fibers between 2013-2016 [59].

### 2.3.2 Polyamide consumption

PA consumption has been increasing globally in recent years owing to its increased usage in varied end-segment industries including electronics, furniture, automobiles and other consumer goods.

Total Polyamide consumption for the year 2016 was 7.4 MTs among which PA fiber & films held the major share of 55% having its consumption majorly in the textile industry for sportswear, clothing & protection clothes [59].

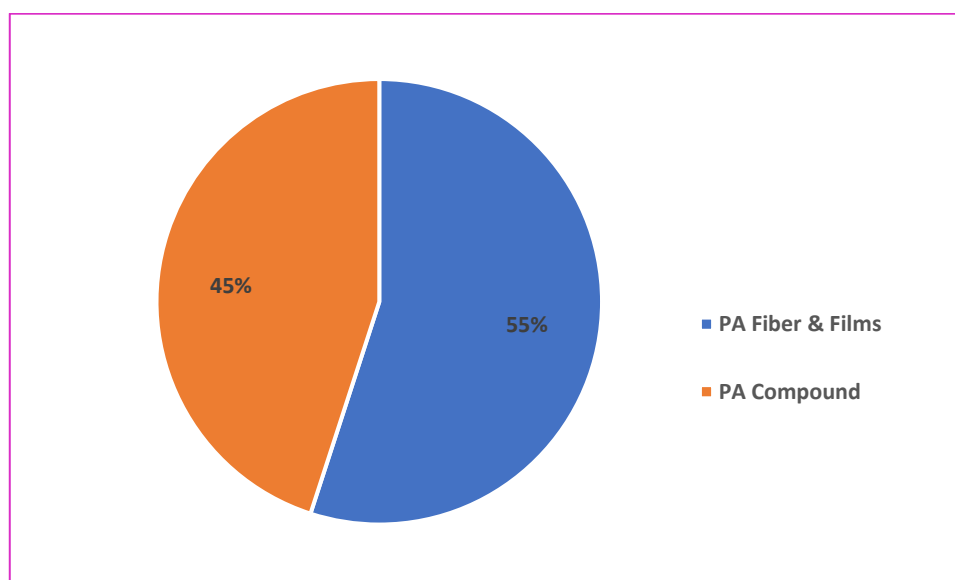


Figure 17. Global consumption of polyamide (PA6 & PA66) by application in 2016 [59].

PA fibers are facing strong competition from Polyesters in different usage areas. Though polyester is cheaper in production but still due to high-quality performance PA polymers are preferred for a number of applications. These materials are processed into textile Filament (NTF), industrial filament (NIF) and carpet filament (PA BCF) and are highly demanded for production of carpets, airbags, seat belt, tire cord, ropes, sewing thread, nets, sleeping bags, tarpaulins, and nets etc [59].

European countries hold a major share in the global sales of these textile filament yarns, primarily The Western European countries. Italy is the leading country among others with the annual sales of 55,589 Thousand Kilograms in the year 2016 (Figure 18). It is followed by Spain with sales of 7512 thousand kg & Estonia with the sale amount of 2406 thousand kg in 2016.

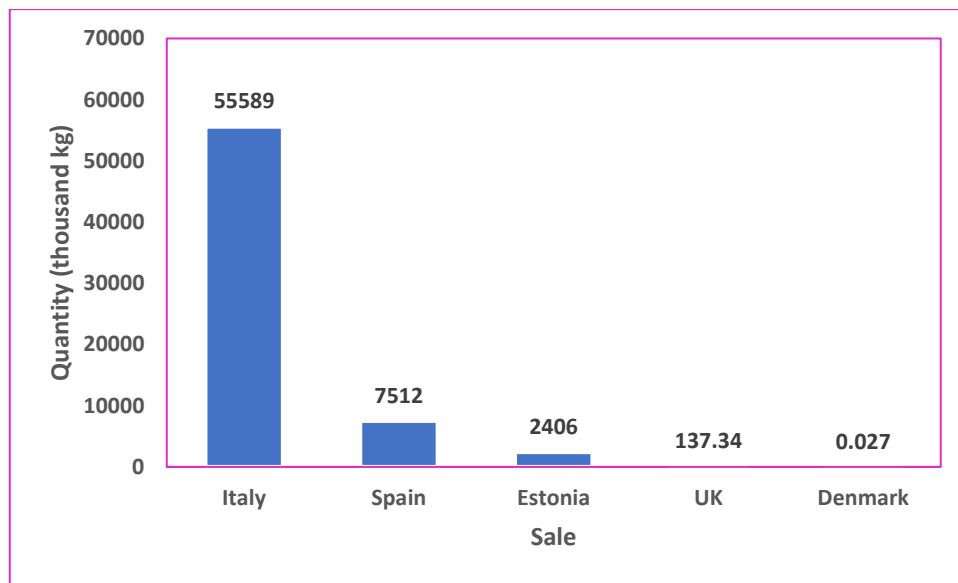


Figure 18. Polyamide textile filament yarn sales in Europe, 2016 [59].

Technical PA compounds global demand share was 45% in 2016 based on PA6 and PA66. The most important application industries are automotive engineering as well as the electrical & electronics (Figure 19). Ceresana forecasts the highest growth rate between 2014 and 2022 for the second largest application area electrical applications and electronics that is likely to see market volume increase by 4.3% p.a. [61].

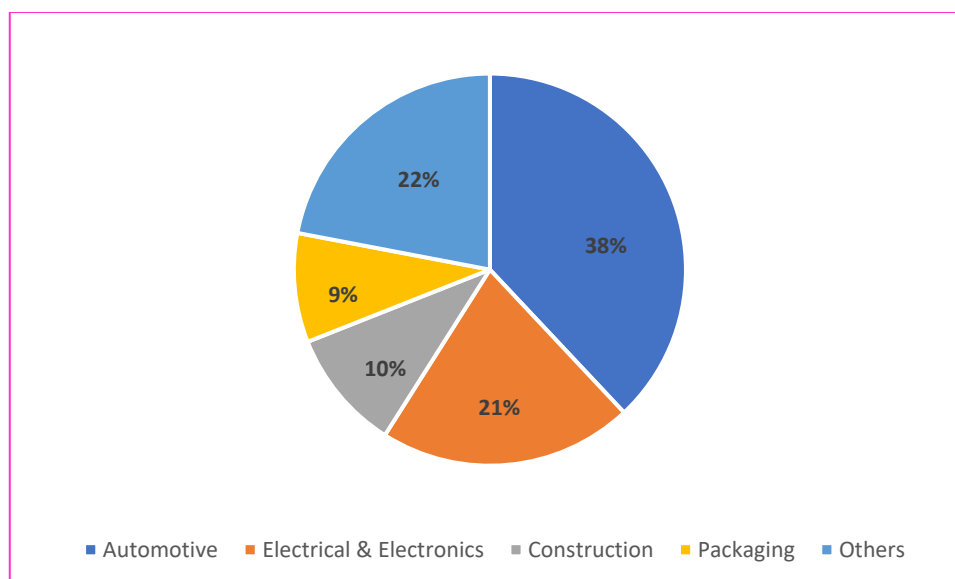


Figure 19. Polyamide demand in Europe in 2014, according to application [62].

The total global consumption of polyamide was 7.4 million tonnes with Asian region leading consumer of the polymer. Asian- Pacific regions dominate the global market demand with holding the total share of 59% in the total demand for the year 2016 (Figure 20).

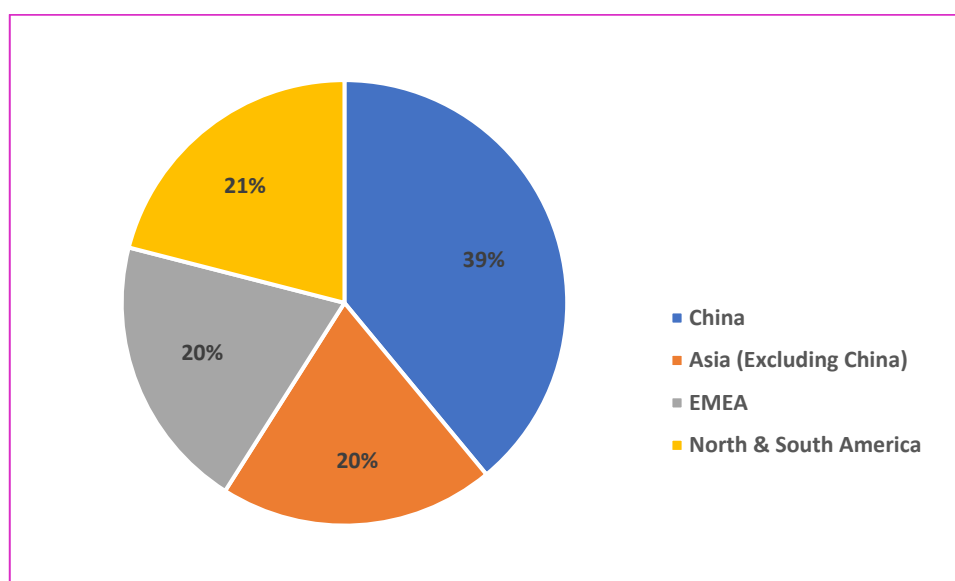


Figure 20. Polyamide demand by region in 2016 [62].

The global market has witnessed high growth in the Asian-Pacific regions due to increased usage of these materials in end segment industries including automotive, electronics, packaging, textiles, building and construction etc. Among all the Asian-Pacific regions, China has the maximum share in the global market demand due to rising population, improvement in financial status and increased consumer demands (like luxury cars). China holds a market share of 39% in the total market demand for the year 2016 and remaining

Asian regions hold 20% of the market share. Asian-Pacific regions are further followed by American regions (North & South America) with the share of 21% of the total market demand. These regions have also witnessed a rise in demand due to increased usage in automobile & electronics market.

The Europe & Middle East African countries (EMEA) are expected to experience higher growth in coming years owing to its increased auto sales, rising construction activities & initiatives were taken by the government for improved infrastructure. In the year 2016, these regions contributed up to 20% of the total market demand.

The current global market situation varies considerably for PA and PA66. The biggest share of PA6 in 2015 went to the production of fibers (58%), whereas most of the PA66 produced went into compounding (60%). The consumption of PA6 compounds increased, growing in all regions, principally through the positive expansion of the automotive industry. Compounds make up about a third of the overall global consumption of PA6. In the case of PA66, about 2.3 million tonnes was produced and sold in 2015; about 1.5 million tonnes of this was for compounds. The biggest producer and consumer of PA66 was North America, closely followed by Asia and Europe.

As mentioned earlier PA6 and PA66 made up most of the PA market. The share held by PA specialties, such as long-chain polyamides (LCPA) and polyphthalamides (PPA) is still small, despite the continuation of relatively high growth rates. In Europe, it constitutes less than 5% of the market [62].

According to MarketWatch, the global specialty polyamides market is segmented by polyamide type into polyamide 610, polyamide 612, polyamide 46, polyamide 10, polyamide 11 and polyamide 12. Specialty polyamides market is anticipated to mask a CAGR of 6.8% during the forecast period of 2018-2027 [63].

Specialty polyamides are bio-degradable and possess relatively superior properties such as rigidity, strength, and other chemical and thermal properties, which make suitable for several different applications. Moreover, they are lightweight. Transportation and consumer goods are main end-markets of specialty polyamides with the market share of 27 and 19%, respectively [58].

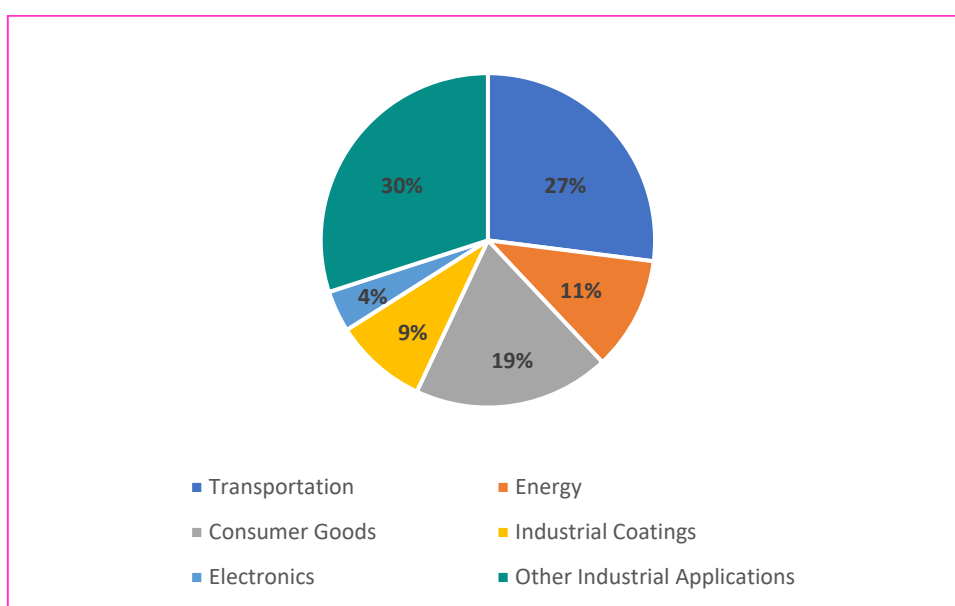


Figure 21. Sales by end-market of specialty polyamides in 2012 [58].

Currently the global specialty polyamides market is observing vibrant growth on account of increasing demand of polymer foams in the market. Advances in material industry in the past few years and growing technological combination explorations are projected to drive specialty polyamides market besides the wide range of functions of specialty polyamides in an immense range of products such as powder coating, resins, alloys, hot melt adhesives, thermoplastic elastomer and more during the forecast period. As a precursor to highly flexible, abrasion resistant polyamides in polymer industry, North America is panned to observe substantial growth in specialty polyamides market due to rising specialty polyamides usage in automotive industry. North America is expected to be followed by Asia-Pacific in terms of consumption due to expanding demand for specialty polyamides in consumer goods and electronics industries. Europe is expected to drive demand and positively impact the growth of specialty polyamides market over the forecast period owing to increasing specialty polyamides application for electrical and electronic components, metal coating and in medical devices and catheters [64].

The rising demand for specialty polyamides and its products for various processes in medical, electronics, consumer goods, industrial coating, automotive industries are expected to drive the market rapidly over the forecast period. Stringent governmental regulations to promote eco-friendly materials are predicted to help the specialty polyamides market grow further during the forecast period. Major companies identified in this industry include Evonik Industries AG, Koninklijke DSM N.V. BASF SE, Arkema, Radici Group, and E. I. du Pont de Nemours and Company among others.

Besides new monomer and polymer capacities in the growth regions, the PA manufacturers are continuing to invest in the construction and expansion of plants for tailored compounds in order to participate in the growing market for compounds [62].

### 2.3.3 Polyamides by application

**Automotive.** The global increase in car production is crucial to the growth of polyamide. Polyamides are often used to replace metal being used in automotive parts where there is an essential requirement of design, flexibility as well as temperature and chemical resistance. It is commonly used to manufacture automotive parts from parts for the engine compartment, via structural and decorative elements in the interior through to body parts and electronic components. The most important growth drivers are weight saving to reduce emissions, higher continuous service temperatures close to modern supercharged IC engines, miniaturization, design and, of course, cost reduction [62].

Particularly in the engine compartment, polyamides have a long tradition, where, for years, they have replaced more and more parts that were hitherto made of metal. Their lower weight compared with metals, and the possibility of functional integration and greater design freedom make this material an attractive, economic alternative. In the recent years, heat-resistant and oil-resistant PA compounds, such as glass fiber-reinforced PA66, have been developed which can be found in a wide variety of car models.

Lightweight construction, structural design and functional integration with polyamides continue to be in vogue in the chassis and in the interior. Glass-fiber, and increasingly carbon-fiber, based compounds specially tailored to the application are now available to the automotive industry.

In airbag containers, PA6 offers parts integration and reduced weight compared to metal containers. Containers made of PA6 do not splinter at low temperatures, as do some other polymers. Today automotive

air intake manifolds are often fabricated from 30-35% glass-reinforced PA6. PA66 and PA46 are also used in manifolds. Substituting metal in the manifolds with polyamide reduces production costs by up to 30%, reduces the weight of the part up to 50%, cuts system costs through parts integration and contributes to higher fuel efficiency. PA12 is used in fuel lines, while PA612 is found in hydraulic clutch lines [65].

**Electrical and Electronics.** Polyamides especially PA6 is highly used for a number of electronic applications like low voltage switch gears, circuit breakers, contactors, connectors, tubes used in wiring & cable protection and others. Polyamide 66 has long been a material of choice in electronic connectors. However, it is giving way to PA46 in this application because connectors are increasingly exposed to high temperatures. This is especially the case as lead-free soldering continues to advance in the industry [59].

PA filled with electrically conductive materials can provide antistatic discharge (ESD) and EMI/RFI shielding for electronic equipment, as well as for trays and conveyer systems used in the manufacture of semiconductor chips.

**Films and Coatings.** In the packaging business polyamides are primarily used in the form of film. Single polyamide film is rarely used, but a common application is in multilayer, transparent foil combined with other polymeric film of polyethylene, polypropylene or poly(vinyl alcohol). In such films for the packing of perishable alimentary products like cheese, meat etc, the polyamide layer provides a good barrier that prevents oxygen penetration as well as loss of humidity and aroma. The polyamide component adds stability to the multilayer structure. Food packaging polyamide films offer toughness, high tensile strength and elastic modulus, flex-crack resistance, low gas permeability and low odor transmission. Film of high brilliance and clarity, particularly from PA11, is available for point-of-sale displays. Due to their polar characteristics, they can be printed without surface treatments, so are often used as outer layers in laminated films. The present trend in households of using small packaging units for ready-made food is expected to bolster the demand for polyamides in film manufacture in the coming years [66].

Medical applications include packages for surgical instruments and blister packs for tablets. Examples of other miscellaneous applications are bags for aggressive chemical products, novelty balloons filled with helium gas and book covers [57].

PA11 is also used in powder form in spraying and fluidized bed dipping to produce chemical-resistant coatings. Although more expensive than the polyolefin and PVC powders, it is of interest because of its hardness, abrasion resistance and petrol resistance [57].

**Construction.** Polyamide resins also find use in building. Simple stuff like door handles, pins and handrails are often made of PA, yet more advanced products are also an outlet, like special long-life, UV-resistant, weatherproof fastening elements [66]. Photovoltaics have opened a new avenue of application for polyamides. Several new grades of polyamides have recently been approved for use in the construction of photovoltaic modules.

**Others.** The list of other possible applications for polyamides is quite long, with the following being a few examples of established, common uses: gear wheels, machinery parts, pressure pipes, wheels for prams, fishing lines, monofilaments for brushes, strings for tennis rackets, aerosol containers, blood bags, syringe catheters and many more. Figure 22 provides examples of application of specialty polyamides in different end-markets. Extensive research is devoted to finding new material combinations and new fields of use,

which demonstrates the great versatility of these materials, whose properties can be very successfully adapted to specific requirements in other areas [66]. An example might be the interest shown in polyamides by the furniture designers Bouroullec brothers, who designed the so-called “Chairs plant”. Most of the examples of polyamide materials above point at physically or chemically modified PA6 and PA66. Other polyamides also come into play. Semi-aromatic polyamides based on poly(phthalamide) are used in the automotive industry. Long chain polyamides like PA12 are replacing PA6 and PA66 in products in which durability and dimensional stability in varying weather conditions are the challenge. They are used mainly in situations requiring very specific characteristics and in situations where their characteristics and wide area of usage is more important than the price. The same is true of another group called bio-polyamides, which are based on natural renewable resources.



Figure 22. Examples of end market applications of specialty polyamides [58].

The dominating polymer is the long-chain polyamide PA11. The largest producer of the material is Arkema SA, which derives it from castor oil. Other representatives in the group are polyamides PA610, PA612, PA1010 and PA1012. The polymers are an interesting complement to the classical crude-oil derived polyamides. In some specific applications they compete with the classical ones, while in other niche uses, they target high quality demands, surpassing PA6 and PA66. Worth mentioning is the environmental aspect of the use of bio-polyamides. Both the material and production technologies are environment-friendly. Prices higher in comparison to crude-oil derived polymers presently pose a barrier for wider use, which may change in the future with the rising prices of the classical materials and tax relief, privileging natural materials. Their increasing use will certainly depend upon interesting properties and new possible

application areas. The emerging possibility of blending nature-derived polymers with fossil derived ones may bring such a chance. The blending may also lead to favourable price/ output/ quality proportions [67].



## 3 PLASTIC WASTE GENERATION IN EUROPE

### 3.1 GENERAL OVERVIEW

The plastics demand in Europe was 50.7 million tonnes in 2019 with an increase of 1.6% with respect to 2016. In Europe, plastic waste collection rate also (EU28+NO/CH) increased from 27.1 MTs in 2016 to 29.1 MTs in 2019 (Figure 23).

Since 2006, the amount of plastic waste sent to recycling has doubled, however 25% of plastic post-consumer waste was still sent to landfill in 2018 (Figure 24). Plastic waste exports outside the EU have decreased by 39% from 2016 to 2019 [1]. The demand corresponds to all plastic materials used in one year to make products, but not all of this becomes plastic waste during the same year.

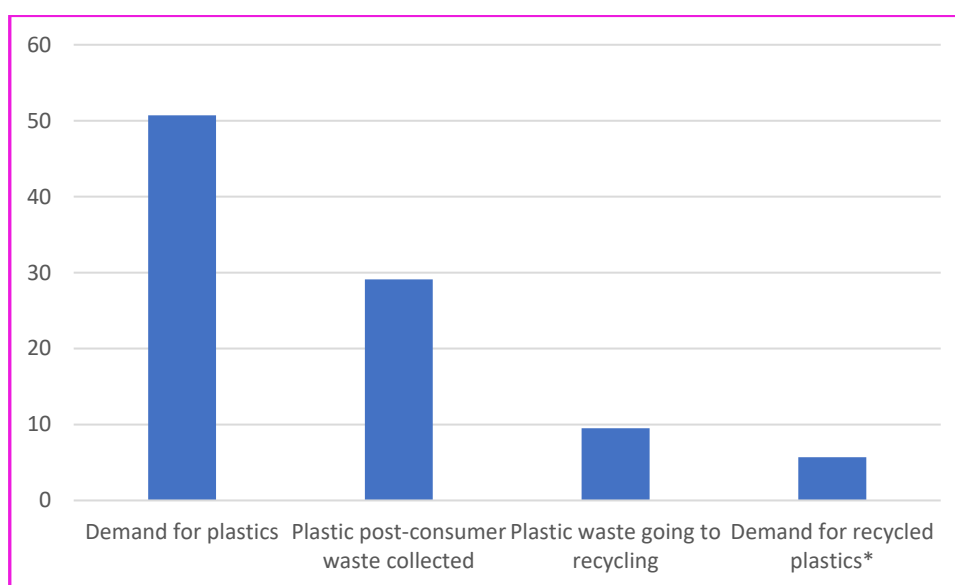


Figure 23. From plastics demand to recycled plastics demand, 2019, MTs [1, 69].

\*KPMG report.

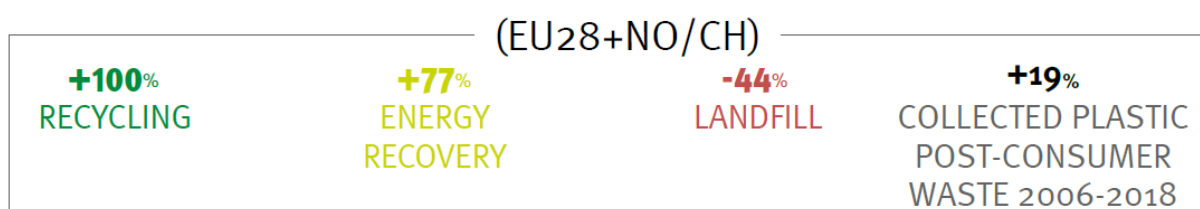


Figure 24. 2006-2018 evolution of plastic post-consumer waste treatment [1].

Plastic packaging, which has a shorter lifetime (a few days to a few weeks), quickly becomes waste and accounts for a large share of plastic waste in the EU (Figure 25). But many plastic articles have a longer lifetime, more than 1 year (e.g. construction materials, automotive parts, household appliances etc.). This plastic waste becomes available only after several years, and for various reasons, is often more difficult to recycle.

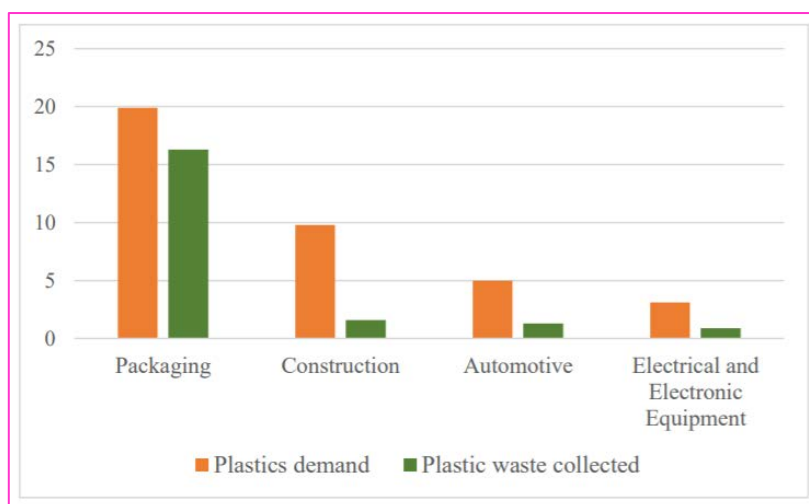


Figure 25. Plastics demand vs. plastic waste collected in the four main economic sectors using plastics, 2016, MTs [69].

The total volume of polymers in collected EU waste in 2005 and 2015 are described below for each waste stream.

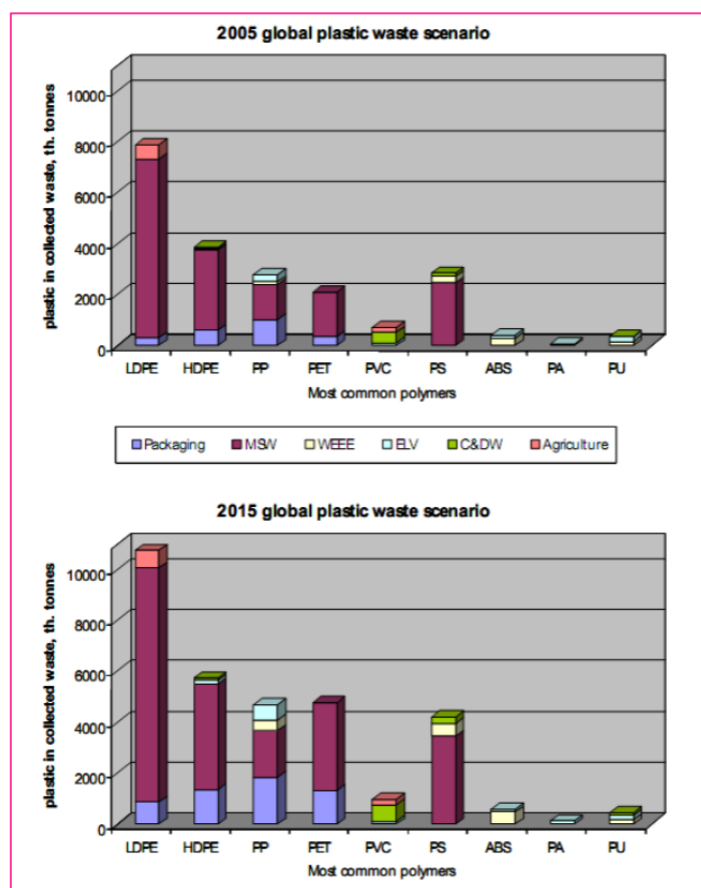


Figure 26. Estimations of the volumes of most common polymers in total waste (EU in 2005 and 2015) [70].

## 3.2 POLYOLEFIN WASTE STREAMS

### 3.2.1 Polyethylene (PE)

Short life packaging applications accounted for 66% of the PE consumption in Europe in 2017. Due to their lifespan, it is expected to enter the waste stream within one year or less after production. Therefore nearly 10 MTs of PE packaging materials entered the waste stream in 2017. This excludes volumes of recyclate which may be incorporated in some of this packaging. This large volume of packaging waste with variety of film types including agricultural waste films, food packaging, industrial, transportation and protection films present a real challenge for recycling.

Most other PE applications have longer lifetimes, and these volumes, other than production scrap, do not enter the waste stream so fast. Just over 1 MT of HDPE were converted into pipes in 2017 which have an expected lifespan of 30-50+ years depending on specific application. Moulded products have the same behaviour, which last for several years. Of the PE applications, a certain volume can be discounted from potential recycling volumes. Waste and refuse sacks by their very nature, end up in the general waste stream, and go to landfill or incineration with the waste they hold.

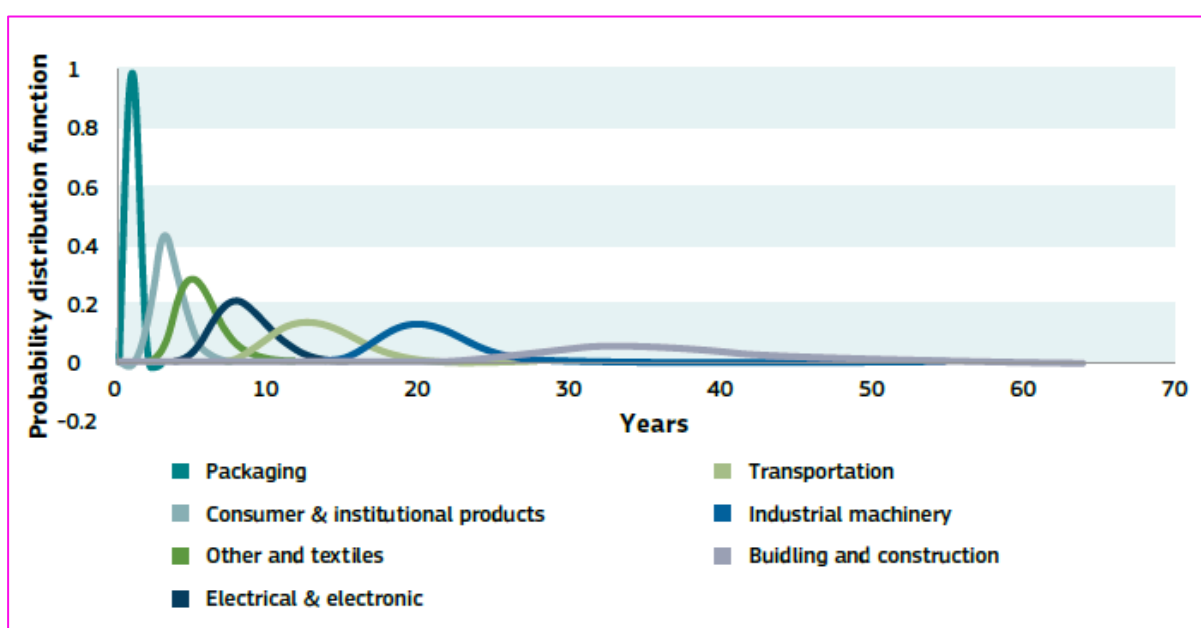


Figure 27. Lifespan of different plastic end-user applications [71].

On the other hand, the level of flexible packaging entering the recycling stream are largely dependent on household waste collection systems, which are widely varied among EU countries and regions. Although multilayer packaging has received an increased demand and complexity recent years, monolayer solutions are clearly better for recycling, even if they have laminated structures. As recycling of multilayer packaging is not feasible at least right now, they have been exported, incinerated or landfilled. To meet EU targets of 55% packaging recycling rates by 2030, capacity to recycle these films need to be found in Europe.

But industrial flexible packaging applications, for example shrink and stretch film, are more likely to find their way into the recycling stream, as large volume can be collected from commercial businesses that require less sorting and processing during the recycling.

Agricultural film is also a source of PE recycling; however, contamination level of films is high due to mud, sand and other impurities which requires a high level of cleaning ahead of recycling.

In addition, production scrap is a large source of waste, where cuttings, rejects or unsold stock etc. can present around 10% of production. Large amounts of production scrap go to recycling companies every year.

Although a large proportion of PE waste is flexible, rigid applications such as HDPE bottles are also readily recyclable. In Europe, cable industry is currently moving towards sustainability and better treatment of the environment. This should see an increase in both the volume of cable jacketing that is recycled and potentially more closed loop within the cables industry.

The majority of PE waste comes from municipal and commercial sources, with the latter being the main source (Figure 28). Based on AMI's analysis, Europe produced just over 2.4 MTs of PE recyclate in 2017. As the emphasize of EU 2030 targets are on packaging applications, the largest increase in the sources of waste is expected in the municipal and commercial sectors, where a 12.2% p.a. increase will be seen to 2030.

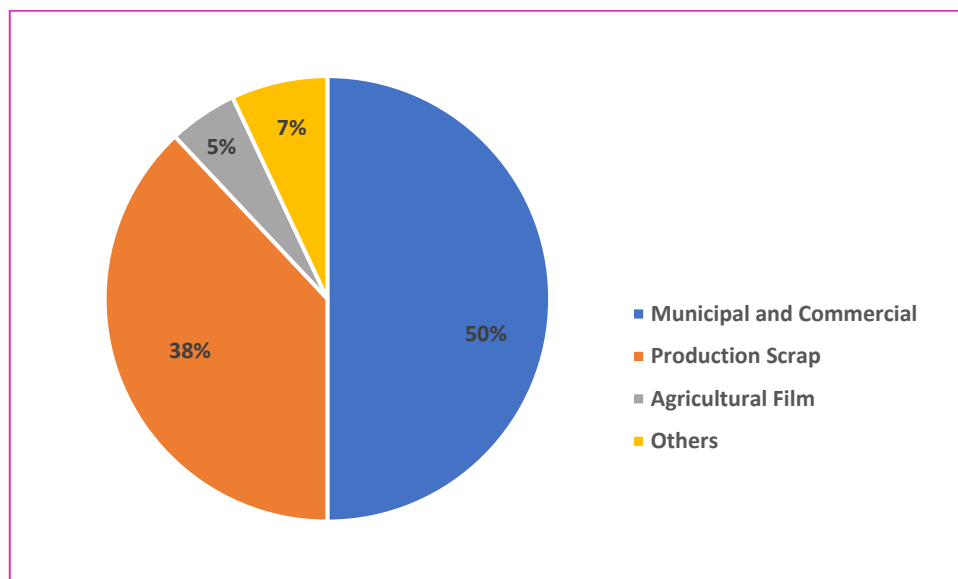


Figure 28. Sources of waste for PE recyclate in 2017 [72].

Germany with its long-standing recycling policies dominates the European PE recycling industry by its 472 thousand tonnes of recycled PE, followed by UK and Spain due to their well-established HDPE milk bottle recycling industry and large agriculture industry, respectively.

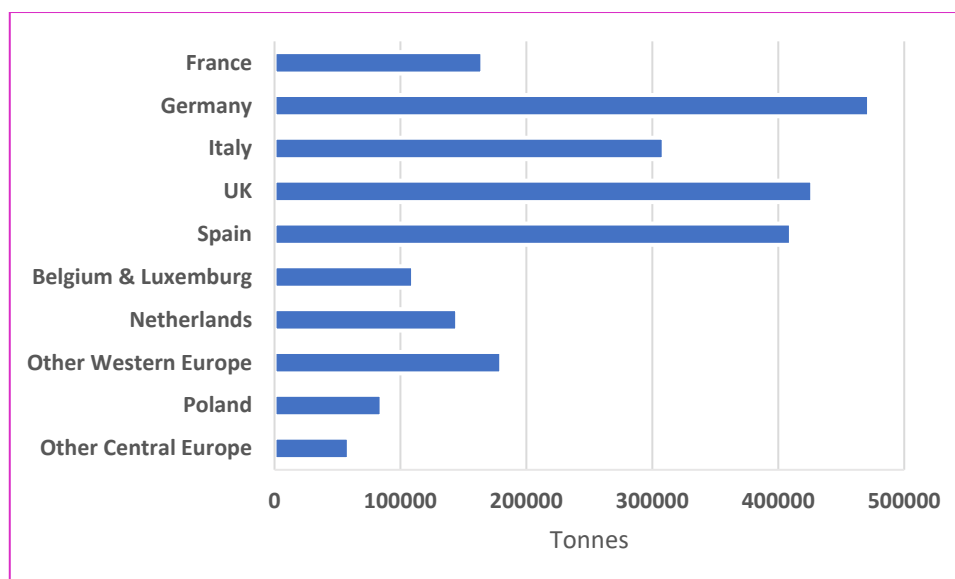


Figure 29. Volumes of PE recylate produced by country in 2017 [72].

According to AMI, there was close to 2.8 MTs of PE recycling capacity in Europe in 2017. By 2030, Europe is expected to require nearly 7 MT of PE capacity to meet recycling targets. This means that not only does the recycling industry need to expand to produce an additional 4.3 MTs of recylate, but that end-users will need to absorb this volume of rPE into their products.

Where most countries require considerable capacity enhancements, the Netherlands is forecast to only require a marginal increase in capacity (Table 4).

Table 4. European PE recycling capacities 2017 & 2030 [72].

Country	PE Capacity 2017 (thousand tonnes)	Required Capacity 2030 (thousand tonnes)
Other Central Europe	85	325
Poland	100	340
Other Western Europe	220	415
Netherlands	170	175
Belgium & Luxembourg	120	345
Spain	450	600
UK	460	1,060
Italy	370	785
Germany	550	1,480
France	180	940
Nordic Region	55	450
Total	2,760	6,915

### 3.2.2 Polypropylene (PP)

The largest market for PP is rigid packaging where it is largely used for caps and closures, crates, thin wall containers and lidded pails. PP has been steadily taking market share from HDPE and PS in these applications. The market has also been driven by improving automotive production and increased demand for consumer goods as a result of the knock-on effect of lower oil prices.

The PP market will largely be driven by packaging applications across the continent while Central Europe will benefit from continuing investments in automotive manufacturing. PP market growth is expected to be 2.6% per year to 2030, increasing annual demand to nearly 13 MTs.

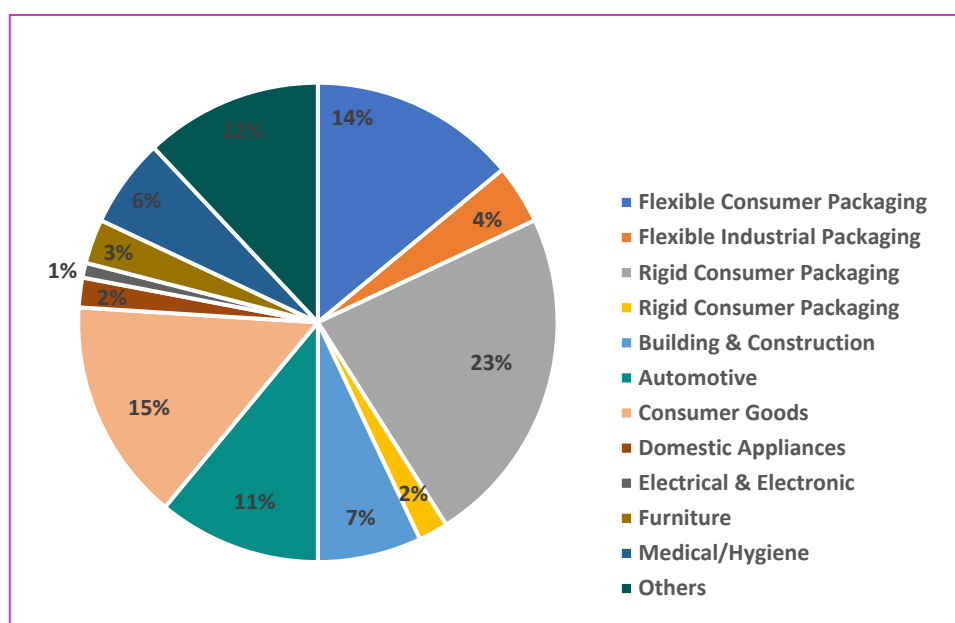


Figure 30. End-use applications of PP in 2017 [72].

Short life packaging applications for food and beverage markets, as with PE, are expected to enter the waste stream within one year or less after production. Some packaging applications however, do not fit this general rule of thumb such as packaging for cosmetics, aseptic medical packaging and some industrial fiber applications, having longer lifespans, usually between one and three years.

Total packaging applications accounted for 43% of PP usage in 2017, and are assumed to enter the waste stream between 0-3 years after production.

Moreover, building and construction applications are designed for a lifespan of 30-50+ years, account for 7% of PP demand. Accounting for 11% of PP demand in 2017, the automotive industry is seeing increased pressure to recycle components parts. Plastics currently make up, on average 15-20% of a vehicle, however as the majority of vehicles entering the ELV waste stream in 2017 will have been manufactured in the previous 10-15 years, it is reasonable to assume they will have less plastic, as during that period, the use of plastic in vehicles has risen to its current volume. Therefore, an assumption has been made that on average 10-15% of the volume of a vehicle entering ELV in 2017 was plastic. Considering the plastic within a car, on average, PP makes up 50%. The European ELV, WEEE and RoHS Directives, all set out collection targets along with recycling and recovery goals to be met by member states which boost plastic recycling including

PP. Although those targets will increase in the next years, volumes of plastics recovered, in particular WEEE, remain relatively low due to the difficulties in decontamination and reprocessing.

Fiber applications accounted for over 1,8 MTs of PP in 2017. Applications include textile, apparel, agricultural/geotextiles and packaging, while lifespans vary depending on specific applications.

According to AMI analysis, Europe currently has 1.9 MT of capacity for recycling PP. Due the wide range of products made from PP, over 50% of waste comes from sources other than municipal/commercial and production scrap. Therefore, “other volumes” is the largest source of waste for PP recyclate. As the need to meet EU 2030 targets for recycling begins to drive improvements to collection services, the volumes of post-consumer PP waste packaging are expected to rise, attributing for the 10.3% per year growth rate forecast to 2030.

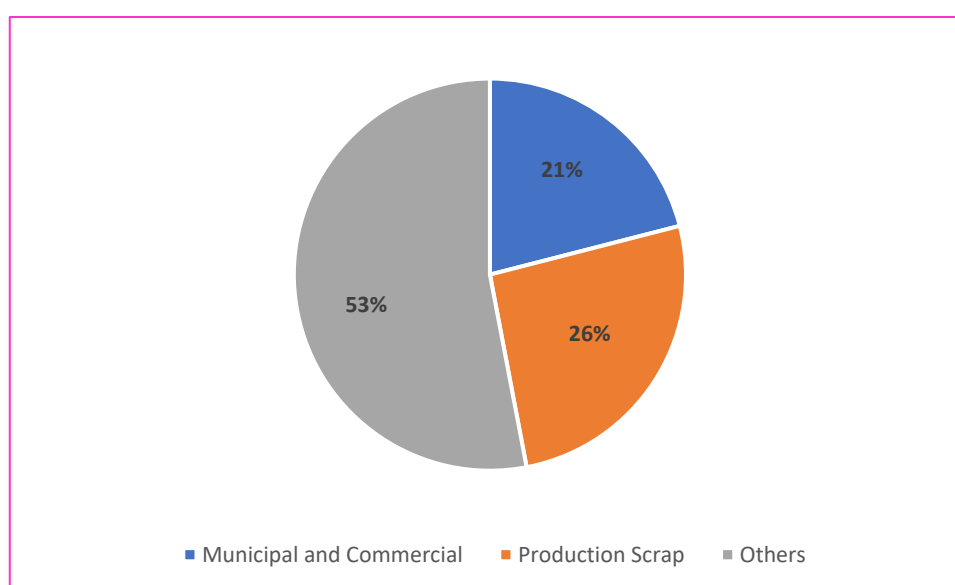


Figure 31. Sources of waste for PP recyclate in 2017 [72].

The total volume of EU PP recyclate produced in 2017 was 1.6 MT. This works out to 17% of volume of virgin PP consumed within Europe (9.3 MTs) and 18.4% of the presumed volume of PP entering the waste stream.

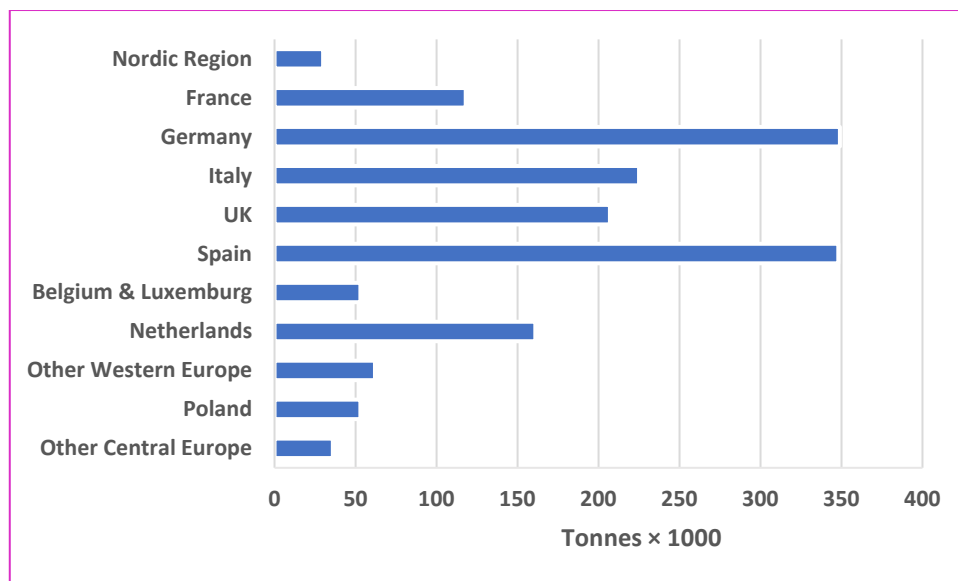


Figure 32. Volumes of PP recylate produced by country 2017 [72].

Germany and Spain are comparable in the volumes of rPP, producing 390,000 and 370,000 tonnes, respectively. They house the largest automotive industries in Europe, and therefore the volumes of automotive scrap recycled are high.

There is currently 1.9 MTs of PP recycling capacity in Europe. By 2030 Europe is expected to require 3.6 MTs of PP recycling capacity to meet targets, an additional 1.7MTs.

### 3.3 POLYURETHANE WASTE STREAMS

#### 3.3.1 Introduction

The end-of-life treatment of products containing large quantities of polyurethane foam is expected to change significantly in the near future. One ecologically favourable change will be that huge quantities of plastic waste will no longer be landfilled but treated in recycling or energy recovery facilities (i.e. incinerated). The EU has set its member-states a target of reducing landfill to a maximum of 10% of municipal waste by 2030. Currently, around 30% of post-consumer plastic waste is still being landfilled so it is a challenging target. Recycling plastic waste is always the preferred option, with energy recovery the alternative for plastics that cannot be sustainably recycled.

#### 3.3.2 Flexible polyurethane

The market sector for flexible PU foam has two major sales outlets, furniture and bedding. Presently, these market sections are not regulated in the EU however, national regulations do exist. End of life foam is part of household “bulky” waste and is mostly collected through road side collection by the local waste authority. The comfort foam market is the largest outlet for flexible PU foam with more than 0.5 MTs. Compared to bedding, the market size of furniture is more than double [73].

Results of a study show that around 30 million mattresses currently reach the end of their life every year in the EU. This represents around 460 kilo tonnes of material, of which 160 kilo tonnes are PU foam. The



annual estimate for end-of-life upholstered furniture is of around 1450 kilo tonnes which corresponds to 450 kilo tonnes of PU foam [74].

Another research in UK highlights that from approximately 5.9 million End of Life (EoL) mattresses, weighing an estimated 148,000 tonnes, which were recovered or disposed of in the UK during 2014, only around 16% of these mattresses were recycled, 11% incinerated with energy recovery and 73% landfilled. Furthermore, 1.5 mattresses are recycled per year for every 100 people in the UK [75].

Furthermore, according to European Federation of Furniture Manufacturers (UEA) statistics, total annual EU28 furniture waste equates to 10.78 million tonnes, from which 80% to 90% is incinerated or sent to landfill, and  $\approx 10\%$  is recycled [76].

Plastics are used for a variety of parts and functions in automotive vehicles. The biggest share of plastic used goes into the passenger cell (the interior of the vehicle), followed by the vehicle's bodywork. On average, plastics account for around 9-12% of a vehicle's weight, or around 150-180 kg, of which about 20% is composite material (i.e. plastic mixed with other materials).

The most common automotive plastic types are PP, PE, PU and PVC. PU is commonly used in seat foam. The weight percentages of most common polymers in current and future plastic waste in End-of-Life Vehicles (ELVs) have been estimated as follows by JRC-IPTS:

**Table 5. Most common polymers in ELV waste [77].**

Plastic type	Current use	Future use
PP	28-33%	38-43%
PU	17-22%	8-13%
ABS	12-17%	5-10%
PVC	8-13%	5-10%
PA	4-9%	6-11%
HDPE	3-8%	7-12%

Contrary to most plastic products, which have in most cases a rather short use-phase, the average lifespan of a mattress in Europe is about 12 years and is much longer for upholstered furniture (up to several decades) [74]. Products with higher life times are promising from sustainability point of view. However, extending the use-phase to ten years or more is also challenging for most products as they mostly contain substances that have been banned, restricted or phased out during the use-phase (so-called legacy substances).

When a substance has been banned by legislation, it means that (EoL) PU foam containing such substances must not be placed on the market anymore. One can conclude that the longer the use-phase the more difficult it is to re-use or recycle the EoL material. A use-phase of many years could even make it impossible to re-use or recycle the EoL material. On the other hand, flexible PU foam being a cellular material has a very important volume compared to its weight (around 20-40 kg/m<sup>3</sup> on average). This means that transporting bulk or compressed PU foam is equivalent to transporting higher amounts of air. This in turn means that cost and environmental impact will be a limiting factor for the long-distance road transport of a material such as EoL PU foam that does not have an important intrinsic economic value [74].

### 3.3.3 Rigid polyurethane

When PU reaches its end of life after many decades in use, it is mainly landfilled or incinerated (90%) and only a small percentage (10%) is recycled. Together with a large quantity of excavation waste, construction and demolition waste it accounts for about 30% of all waste generated in the European Union [77]. Its lifespan (typically 30 to 75 years or more based on the application) is closely linked to the buildings' renovation cycles. One problem is related to the contamination by others in its use phase (bitumen, adhesives, rust, render, etc.). PU insulation consists of 97 % insulating gas captured in the closed cells of the foam and is therefore extremely light-weight. Its share in the total non-mineral construction and demolition waste should be around 0.3% (figure for Germany) and around 0.05% in the total construction and demolition waste (estimates for France and the UK).

## 3.4 POLYAMIDE WASTE STREAMS

### 3.4.1 Introduction

Recycling and environmental protection are current issues that force us to think about possibility of reprocessing of polymer waste and thus regenerating new products in a closed loop.

### 3.4.2 Polyamide 6 and polyamide 66

The main source of polyamide waste is in the form of fibers, mainly from carpets. Most carpet waste comprises potentially usefully materials such as cotton, polyester (polypropylene) and nylon, and manufacturers, suppliers, recyclers and academic institutions are actively pursuing ways to recycle carpet waste.

Annual post-consumer carpet waste production in Europe is 1.6 MTs, which is 160 times heavier than Eiffel Tower weight [79]. Americans also generate approximately 1.6 MT of carpet waste and 113,000 tonnes of underlay each year, around one percent by weight of municipal solid waste (MSW) [80]. The average life cycle of a carpet is between 8 and 12 years. Carpet production also generates a substantial amount of waste in the form of trimmings and cuts, which typically amounts to 12% of the total production.

Majority of carpet waste (60%) is landfilled in Europe, while 37-39% is incinerated. Only 3% of carpet waste is being recycled.

During production of parts out of cast polyamide 6 (PA6G), waste amounts of up to 15 % arise due to sprues, distribution systems and fluctuations in product quality. Taking post-processing into account, the waste quantity can reach up to 30 % of the used material. Annual waste volumes of cast polyamide in the European Union are estimated to be about 5,000 tons. Typically, cast polyamide waste is thermally recycled although some material recycling is done by mixing it with new extrusion type polyamide. Nevertheless, cast polyamide waste offers a much greater potential for direct material recycling because of its high-quality properties primarily basing on the higher molecular weights.

Polyamides can also be found in the packaging waste. As mentioned earlier, PAs are used in particular in multilayer packaging systems where where exceptional mechanical resistance is needed. In composite or multilayer films, PA6 and copolyamides with PA6 as the main component are used (PA6/66, 6/11 and 6/12).

Since multilayer packaging makes up a large percentage of the packaging market and is currently mostly treated by incineration, it is an option to try reaching the quotas by pursuing a solution for the recyclability dilemma of multilayer packaging.

The replacement of multilayer packaging by monomaterials can be an option for some multilayer systems. However, it is expected that not all kinds of multilayer packaging can be substituted by monomaterials, and functionality, costs, and marketing are still the main drivers of the packaging market. Thus, it may be worthwhile having a closer look at the recycling strategies of multilayered packaging [81].

### 3.4.3 Long-chain polyamides

Due to unique properties of long-chain polyamides such as PA10, PA11 and PA12, they are mostly used in automotive, sport and electrical and electronics segments; collection and sorting of waste streams composed of specialty polyamides are really challenging and difficult as most of those materials are used in niche applications or as coating which makes impossible to collect them.

New applications of those polyamides and polyphthalamides in composites are of interest, taking targeting automotive and transportation) into account, where there is legislation for End-of-Life Vehicles that will force to collect and recycle, and the parts should be more massive. However, this market is not really existing and needs a global solution.

## 4 PLASTIC WASTE TREATMENT IN EUROPE

### 4.1 GENERAL OVERVIEW

In 2018, 29.1 MTs of plastic waste collected for further treatment in the EU28, Norway and Switzerland. According to PlasticsEurope [1], plastic (not only packaging) post-consumer waste was treated in the following way:

- 42.6% Energy recovery
- 32.5% Recycling
- 24.9% Landfill

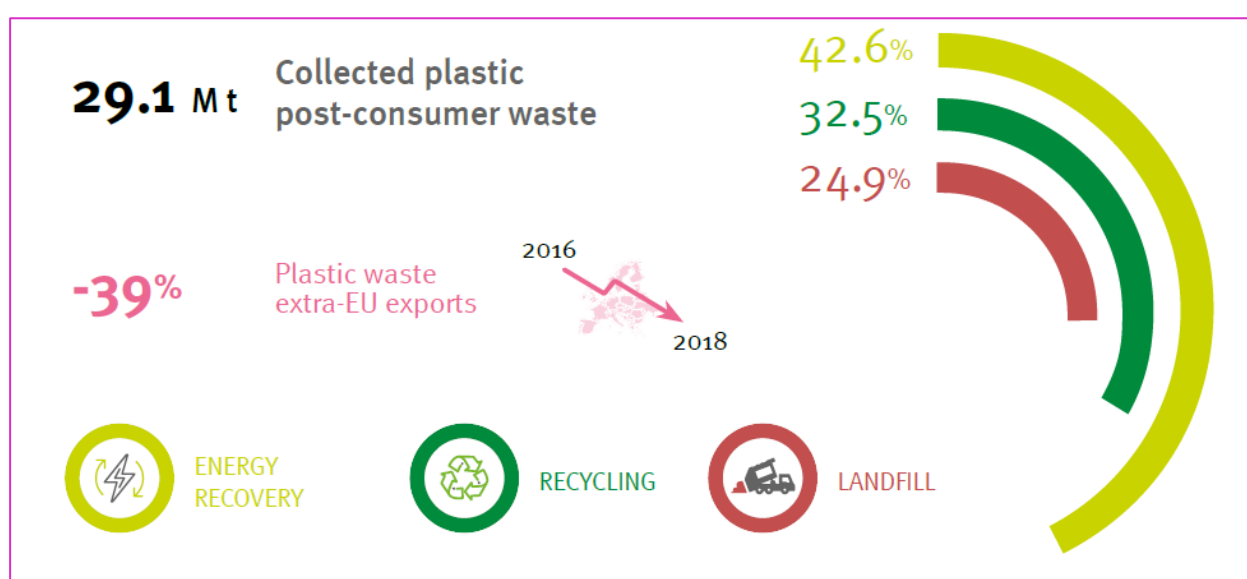


Figure 33. Plastic post-consumer waste treatment in 2018 (EU+NO/CH) [1].

In Europe, it was never the case before 2016 that more plastics were recycled than landfilled. In 2006, the landfill rate for plastics in Europe was still 52%. Therefore, significant progress in diverting plastics away from landfilling has been made. In fact, between 2006 and 2018 plastic recycling grew by almost 100%, whereas energy recovery increased by 77% and landfilling declined by 44%. Furthermore, the total plastic waste collected increased from 24.5 MTs in 2006 to 29.1 MTs in 2018.

Nevertheless, plastic waste management with regard to landfilling practices varies extremely across Europe. In fact, in 2016, eight member states landfilled less than a 10% share of their post-consumer plastic waste, namely Austria, Germany, the Netherlands, Luxembourg, Belgium, Denmark, Sweden and Finland. It is noteworthy that in all of these central and Northern European countries legal restrictions on landfilling exist [82].

In 2017 more than 99% of plastic waste was recovered, with a slight upward trend of 0.4% from 2015 to 2017. However, it is important to note that this initially high number is explained by the following facts: Recycling here does not indicate that the material has been indeed reused in some way, but that it was

collected and provided for recycling (exports included). Material recycling in this statistical approach amounts to 46.7%. Since there is a ban on landfill in Germany, only recycling and incineration are potential ways of plastic waste treatment, hence 99% coverage. The remaining 61 % of the accruing waste was treated by energy recovery. From 2019, the new packaging law will come into force in Germany, which is to lead to recycling rates for plastics of 58.5% by 2019 and 63% by 2022. Thus, a decrease of energy recovery can be expected.

**Table 6. Postconsumer and total plastics waste 2015 & 2017 [83].**

	Post-consumer waste		Total polymer waste	
Year	2015	2017	2015	2017
Recovery rate	99%	99%	99%	99.4%
Energy recovery	61%	60%	53%	52%
Recycling rate	38%	39%	46%	47%
Mechanical recycling	37%	38%	45%	46%
Feedstock recycling	1%	1%	1%	1%
Disposal	1%	1%	1%	1%
Total waste quantity	5.0 MT	5.2 MT	5.92 MT	6.15 MT

In total about 1,764 thousand tonnes of recyclates were used in 2017, which is a share of 12.3%. Significant quantities of recyclates were used especially in agriculture, construction and packaging applications. The recycled contents of these three segments were about 9% for packaging, about 22% in products for construction and about 35% in agricultural applications.

PlasticsEurope argues that landfill bans promote higher recycling rates. Nevertheless, as was pointed out before, landfill bans also foster increased incineration, possibly leading to a lock-in effect. Furthermore, the United Kingdom, Ireland, Estonia and Slovenia deposited up to 30% of plastic waste in landfills. Portugal, Spain, France, Italy and certain Eastern member states, namely Lithuania, Poland, the Czech Republic and Slovakia, landfilled up to 50% of their post-consumer plastic waste. The rest of the Eastern European member states, namely Latvia, Hungary, Croatia, Romania, Bulgaria, and Greece landfilled more than 50% of their plastic waste [1].

Reuse and recycling rates for plastic waste are rather low when compared with materials such as paper, metal or glass, which can be explained by the inherent complexity of plastic. In 2015, the recycling rate of glass amounted to 73% in the EU28, whereas the recycling rate for plastic waste was roughly 31%. The European Commission aims for similar rates for plastic packaging as for other packaging materials in the future [84].

## 4.2 PU WASTE TREATMENT

The demand for PU products is increasing day by day. Consequently, recovery and recycling processes have become important to attend to the pressing demands for more environmentally friendly materials. According to the latest report published by PlasticsEurope, the demand for polyurethane was 7.9% of total demand for plastics in Europe, which implied an annual demand of 4.01 MTs in 2019 [1]. Of the 4.01 MTs, approximately 70% is in the form of foam (1.50 MTs of flexible foam, 1.31 MTs rigid foam), 30% being that of polyurethane elastomers and other products. Of the 2.81 MTs of PU foam, around 27% of waste is generated (700,400 tonnes), of which, 31.1% is recycled, 41.3% is incinerated and the remaining 27.3% is taken to landfill [85].

The sectors according to demand are: Construction and building (24.5%); automotive (19.5%), refrigeration (21.3%) and other sectors within the textile industry, usage in technology, etc. (34.7%) [86].

According to EUROPUR [74], energy recovery today (or waste-to-energy) is the preferred technology for the treatment of EoL polyurethane flexible foam and is the one that is immediately able to divert great volumes of organic waste from landfills. As mentioned in Chapter 3, waste mattresses and upholstered furniture join the so-called solid municipal waste or “bulky” waste streams in Europe (together with the rest of waste furniture and solid household waste for example).

However, the situation in a few European countries like the Netherlands is by now different. In the Netherlands, alone, 1.5 million mattresses are discarded on annual basis, of which approximately 75% are collected and recycled. Only 1 million mattresses were handled by RetourMatras company at 3 of its Dutch locations in 2020.

As regards recovery techniques based on incineration the most important advantage is the possibility of application for polyurethanes that are contaminated, foamed with Freon or permanently linked with wood, leather or fabric. Moreover, combustion and incineration lead to volume reduction of the landfilled waste up to 99%.

The energy recovery from scrap rigid PU foam from construction and demolition waste in co-fired solid waste incineration plants (MSWIs), was initially promoted by Rittmeyer et al. [85a]. Initial tests were conducted in Germany at an incinerator of the Karlsruhe Research Centre and at a full-scale MSWI plant, with specific objectives of measuring the waste burn-out and the emission of combustion pollutants (e.g. CFCs, HF, HCl, dioxins/furans (PCDD/Fs). Emissions of CFC-11 and chloro-fluoromethanes were between 0 and 10  $\mu\text{m}/\text{m}^3$  (against an ambient of  $\approx 4 \mu\text{g}/\text{m}^3$ ).

Furthermore, when high temperatures are applied PU foams can release toxic compounds and carcinogens, like carbon monoxide, hydrogen cyanide and nitrogen oxides [85b,c]. Polyurethanes show much higher toxicity during thermal degradation under aerobic conditions. The amount of emitted nitrogen oxide under aerobic conditions is well above acceptable levels (up to 2.5-fold), while in the case of pyrolysis only slightly exceeds the threshold at 550 °C, and higher temperatures standards are maintained. The gases generated by the combustion may also include isocyanates, which are compounds with high toxicity. Exposure to them can lead to skin, eyes and respiratory system irritation. The last one can be so strong that even 0.02 ppm exposition can lead to so-called isocyanate asthma. Higher levels can cause pneumothorax [85d].

These disadvantages, along with the large amount of waste taken by landfills, prompt a search for alternative ways to recover this type of waste. Over the past decade, European obligations to control the environmental impact of waste incineration (Directive 2000/76/CE) and of landfill of waste (Directive 2008/98/CE) have led to the increased cost of these waste treatment options. These costs will increase as more strict controls are introduced; as taxes on landfill and on incineration increase, this further encourages reuse and/or recycling.

Several studies have researched the option of reusing polyurethane foam waste, combined with pitch binders, and PU foam waste as a dry aggregate in different cement or gypsum matrices [87].

Studies on cement and PU mortars have shown that there is a positive influence of these recycled aggregates on their manufacturing, which ensures excellent durability, even with regard to other traditional aggregates. Previous research has led researchers to think that this polymer is able to reduce the amount of sand in cement mortars by substituting sand with PU by between 13–33% [88], 25–50% [89] or even 25–100% [90], all of these accounting for substitution in volume. The choice of the volume of substitution depends on the characteristics that are desired to be achieved in the final product.

On the other hand, the recycling process for PU is beneficial both in terms of the environmental as well as from an economical point of view. Usually, the recycling process is done under 3 classes: advanced chemical, thermochemical and mechanical recycling [91a].

All these three methods contribute unique advantages to PU fabrication and utilization. Figure 34 lists the applications areas or waste sectors and the recovery and recycling technologies used.

The mechanical recycling process needs physical treatment, whereas chemical and thermochemical recycling need chemical treatment to generate feedstock chemicals for industry. The by-products from the recycling process are non-hazardous and thus are disposable to the environment. However, mechanical and thermochemical recycling and energy recovery are the main pathways to recycle PUs. Usually, mechanical recycling can be achieved by regrounding the PU foams into powder wherein the PU can be used again. The processes used are compression moulding, adhesive pressing and flexible foam bonding. On the other hand, PU granules can be coated with a glue (binder) and further cured under pressure and heat.

This process is carried out to fabricate floor mats and tyres. Pump and mother housing are, however, made by the compression moulding of PU granules under high pressure and heat [13].

Up to 50 000 ton of rebinding foam are processed each year in Western Europe and new applications are constantly being developed. PU foam scrap can be reprocessed by mixing scrap particles (size approx. 1 cm) with diisocyanate MDI followed by form-shaping at 100–200°C and 30–200 bar pressure [19].

PU construction boards with excellent water and moisture resistance are obtained, or insulation panels for use in new refrigerators or freezers. PU foam can likewise be recycled to blocks that find use in carpets, sports hall mats or furniture. The enormous amount of flexible PU foam recovered from scrapped vehicles may satisfy a large part (in the USA almost 50%) of the market of carpet underlay. In 2015, approximately 800 million pounds of flexible polyurethane foam waste (combined post-industrial and end-of-life post-consumer scrap) was recovered in the U.S. and an additional 200 million pounds of scrap was imported,

primarily from Europe. This volume of collected scrap was mechanically processed and used as a raw material feedstock in the manufacture of bonded cushion products [92].

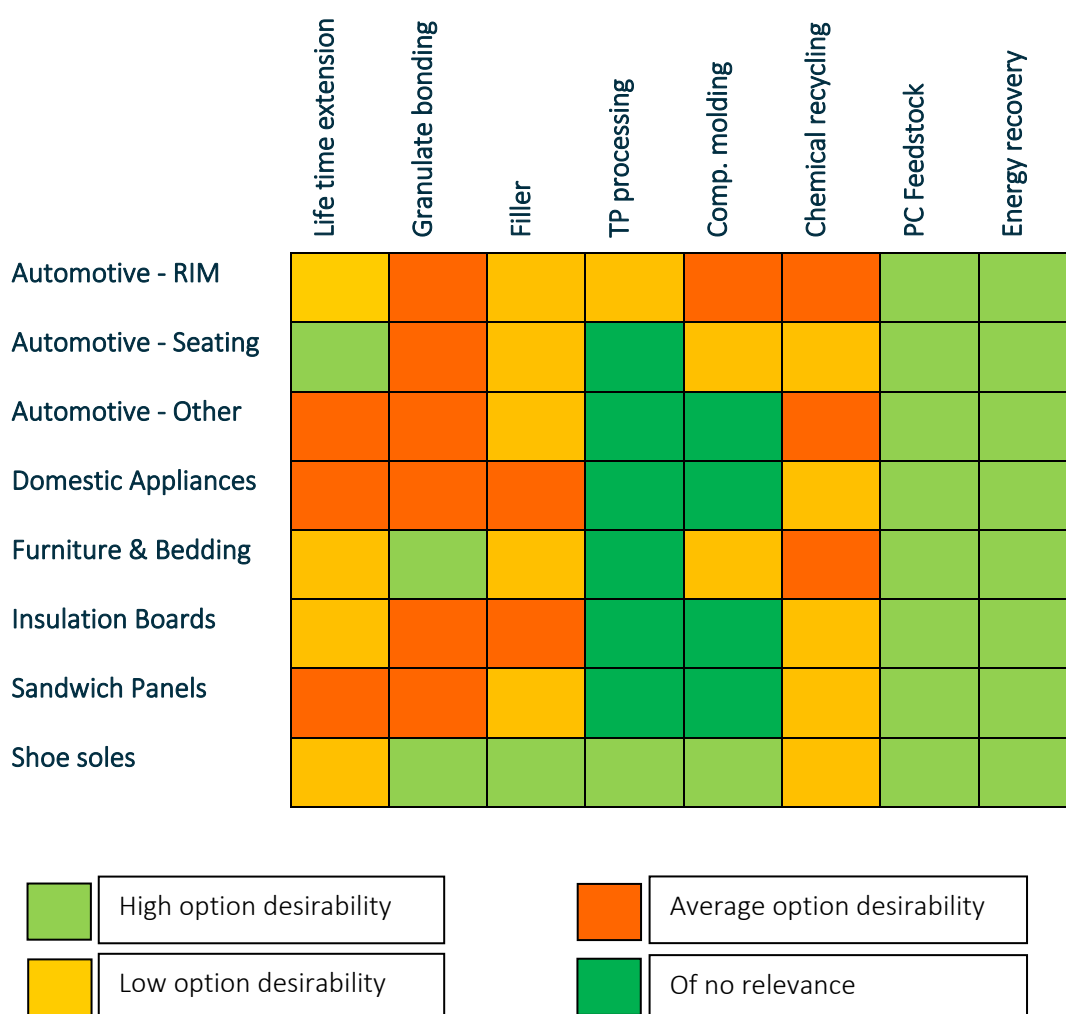


Figure 34. Applications areas/waste sectors and the recycling and recovery technologies which are relevant [73].

Recticel, a foam producer, has a recycling plant in Angers (France) processing post-consumer foams into acoustic insulation panels.

For rigid PU foam from scrapped buildings this recycling option is very important as well but is more complicated and often impossible due to the use of flame retardants in these materials [91].

In particular, the thermochemical and chemical recycling processes are based on several chemical reactions, such as, hydrogenation, pyrolysis, hydrolysis and glycolysis. The recycling process of PU is economical and practical because of the PU's rigid and semi-rigid nature [93]. Hence, recycled PU may be successfully used in the manufacture of quarter panels, wheel covers, steering wheels, bumper covers and cores in automotive vehicles as well as for the manufacture of other domestic and industrial parts.



As the most economic process for PU recycling is the glycolysis process, there are many reports investigating the glycolysis of PU. These reports have discussed different aspects of catalyst effect in glycolysis, physical chemistry of glycolysis process, formulation of glycolysis product, etc. [91a].

It is based on a transesterification reaction in which a hydroxyl group from glycol replaces the ester group containing a carbonyl carbon of a urethane bond. This reaction produces polyols for which the properties can be controlled to some extent, and may be similar to those of original material. They can be used in the production of polyurethanes [91b].

There are two main directions of the glycolysis. The first one leads to the recovery of polyols for the production of flexible polyurethane foam. Second, so-called split-phase glycolysis (SPG) results in rigid and flexible polyols. SPG is based on separate processing of top and bottom layers from diethylene glycol (DEG) glycolysis. The upper layer, mainly comprising the flexible polyols, is washed with DEG, and the lower is treated with propylene oxide resulting in the formation of rigid polyols [91c].

The main limitation of glycolysis is the difference in process parameters for flexible and rigid foams, which enforce segregation of used waste. This method is also significantly more effective when applied to the post-production waste due to the high sensitivity of the reaction to the presence of impurities that may generally occur in consumer waste.

PU is environmentally non-hazardous and more economical compared to other conventional polymers due to its recycling and recovery. Amongst chemical methods of polyurethane recycling, only glycolysis and gasification were implemented on a large scale, while others remained in the research stage.

Today, a small number of glycolysis plants are operating in Europe. They process uncontaminated waste of a known composition, which is mainly production waste. According to the current state-of-the-art, about 30 % of the polyols used in rigid PU foam can come from glycolysis without affecting product quality [94a, b].

Renuva<sup>TM</sup> is a mattress recycling programme launched by Dow which aims to recycle up to 200,000 mattresses a year. Dow partners in the construction of Europe's first chemical recycling plant for post-consumer polyurethane foam in Semoy (France). The Vita Group, which is a foam producer in the Netherlands will use recycled polyol from the plant to make new polyurethane foams as officially announced that in October 2020 [94c].

Many other projects on chemical recycling of polyurethane foam are currently making rapid progress. Early December, RetourMatras and its shareholders Ikea and Renewi Netherland have announced plans to expand the company's recycling capacities with chemical recycling, based on Ikano Industry's glycolysis technology in Poland [94d].

Table 7. Comparison of chemical polyurethane recycling methods.

Treatment	Input	Output	Large scale application
Hydrolysis	EOL products production scraps	polyols, amine intermediates	No
Hydroglycolysis	EOL products, production scraps	polyols	No
Aminolysis	only foams	bi- or polyfunctional amines and alcohols	No
Phosphorolysis	production scraps	phosphorus containing oligourethanes	No
Glycolysis	only foams, segregated for rigid and flexible	polyols	Yes
Gasification	EOL products, production scraps	syngas	Yes
Pyrolysis	EOL products, production scraps	oil, gas, ash	No
Hydrogenation	EOL products, production scraps	Gas, oil	No

### 4.3 PA WASTE TREATMENT

The recycling of polyamide products to conserve materials and minimise landfill is an important business and technical issue, prompted by increasing concerns about the environment and the use of resources [53].

The mechanical recycling process is the easiest way to recycle polyamides. One of the techniques with the potential application is melt extrusion [95]. The mechanical recycling is appropriate from both an economic and environmental point of view. In practice, the contamination with impurities and others polymer as well as the degradation of material are the main difficulties for this method of recycling of polymers. It does depend on having a homogeneous material as even a mixture of polyamide 6 and 66 could give problems. Moreover, it is very difficult to identify and discern with precision PA6 from PA66 [96].

It is essential that recyclates have well-defined and repetitive properties, even after multiple processes. Lozano-González et al. investigated the effect of multiple processes of PA6 by the injection moulding method at a temperature of 235 °C. The authors observed that the physicomechanical properties of the material remained constant until the eighth cycle. Afterwards, during the multiple processes, the percentage of elongation decreased by about 70%, while the molecular weight increased, most likely as a result of the recombination of broken chains [97].

The chemical recycling process is another possibility to reduce the amount of PA waste. The purpose of chemical recycling is to recover and reuse monomers [98]. This method is used for polyamides as well as polyurethanes [98-100] and polyesters [101]. The reactivity of polyamides depends on the polar amide groups present in the main polyamide chain, which can react with decomposing agents. The typical decomposing agents are ammonia (ammonolysis) [102], water or steam (hydrolysis) [103-105] and glycols (glycolysis) [106]. The products of the decomposition of polyamide are oligomers or small-molecular-weight chemical compounds with different physicochemical properties and functionality.

The aim of polyamide depolymerization is to obtain caprolactam and hexamethylenediamine, which can be utilized in the synthesis of new polyamide or other polymers, because their properties resemble those of commercial reagents [103].

Hydrolysis and ammonolysis of polyamide have been widely described in the available literature. Wang and Zhang [104] examined hydrolysis of polyamide 6 in subcritical water. The authors replaced traditionally utilized homogeneous acids with H- form zeolites. Based on the conducted experiments, it was concluded that the temperature and reaction time are the decisive factors of depolymerization via hydrolysis. Moreover, the amount of water used does not affect the disintegration of polyamide. On the basis of their studies, the scientists demonstrated the mechanism of degradation. Firstly, the hydrogen bonds are broken, which is followed by the formation of oligomers as a result of a nucleophilic substitution reaction between water and the carboxyl groups. Patil and Madhamshettiwar [105] optimized the conditions of hydrolytic depolymerization in the acidic medium of PA66. The scientists observed that the most effective reaction is achieved at a temperature of 80 °C, with an excess of acid. A novel, promising method described in the literature is the hydrothermal treatment of waste plastics [107-108].

The aliphatic polyamides are dissolved in super-heated and supercritical water, which results in the hydrolyzed products. With regard to the ammonolysis of polyamide, Kalfas [109] demonstrated the mechanism of PA disintegration, which is based on the breakage of amide bond and the dehydration of amide end-groups.

Recycling of PA was pioneered by the carpet industry as part of a closed loop recycling services [110]. A comparative LCA study of virgin nylon and recycled nylon for carpet manufacturing carried out for Shaw Carpets and reviewed by LBP-GaBi University of Stuttgart highlights the significant environmental improvement potential of recycled polyamide [111]. This is because the production of the feedstock is avoided.

In order to understand the possible availability and quality specifications of PA fibre with a recycled content an attempt was made to identify EU and global manufacturers. Based on the best available information and input from industry associations it can be seen that the number of manufacturers is currently limited.

The following fibre products have been used in clothing products available on the EU market:

- Aquafil (Italy and Slovenia) [112a,b]: PA-6 can also be depolymerized to yield caprolactam. PA-6 from carpets is hydrolyzed with steam by Aquafil in a plant in Slovenia to obtain pure caprolactam recovered by vapor condensation, which is then recycled back to carpets. The Econyl PA6 product is a 100% recycled content product. Pre- (70%) and post- (30%) consumer waste is used as feedstock. The production capacity is understood to be 9,000 tons/annum, although the proportion of recycled product is unspecified. In 2011 the company launched a polyamide textile take-back system. Feedstock includes used fishing nets.
- Hyosung (Taiwan): The MIPAN Regen PA6 product is a 100% recycled content product and is third party certified by the Global Recycled Standard (GRS) [113]. Pre-consumer waste is used as feedstock. Data on production capacity could not be obtained.
- Unifi (USA): The REPREEVE PA66 product is manufactured with 100% recycled content and is solution dyed [114]. Pre- and post-consumer waste is used as feedstock. Data on production

capacity could not be obtained. The recycled content of the fibre is third party certified. In 2011 the company launched a PA textile take-back option for industry production waste.

An US review suggests that recycled polyamide is available in a wider range of deniers than recycled polyester and that dyeability is comparable [115]. Information on comparative mechanical strength and abrasion resistance could not be obtained.

In cooperation with the Institute of Plastics Technology (IKT), Visiotech GmbH is currently developing a recycling process for PA12 waste powder, in which an in-situ regeneration takes place during the selective laser sintering process by coating the powder particles. The production of high-quality plastic components from recycled PA12 powder by means of selective laser sintering processes represents a ground breaking progress. The multiple reuses of recycled PA12 powder and the consequent cost reduction of the selective laser sintering production should enable the development of new markets. Furthermore, the procurement of PA12 new powder can be drastically reduced, thus saving resources and the environment.

The recycled for of PA polymers can be reused for a number of uses such as carpet cushioning, automotive parts, roofing shingles, composite lumber, flooring material, highway noise abatement panels, packaging, and others.

## 5 COSTS OF ALTERNATIVE WASTE TREATMENT OPTIONS

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### 5.1 GENERAL CONSIDERATIONS

The increasing pervasiveness of plastics has not been without drawbacks. The production and disposal of plastics is responsible for significant greenhouse gas emissions and, when poorly managed, generates plastics pollution in the natural environment.

As defined within the Landfill Directive, municipal waste means waste from households, as well as other waste which, because of its nature or composition, is similar to waste from households. The mixed and dispersed nature of municipal waste typically make it difficult to treat.

The management of MSW is one of the most important environmental problems that governments must take on. The increase of MSW is a serious concern for several countries [116]. It implies that strategic planning must be carried out at all stages to ensure a management that minimizes environmental impact. This is especially true since an inadequate decision could have adverse effects on economic, social, legal, and environmental aspects. Selection of the different physical, chemical, biological, or thermal treatments along with landfilling depend directly on the MSW streams' characteristics.

The great variety of available organizational, financial and management schemes, at the local and regional government levels, along with a plethora of continuously developing technological advancements in the design and operation of treatment facilities, renders the economic analysis a complex endeavour. The complexity is further enhanced by the scarcity or unavailability of real cost data.

The costs of different waste management services do not form a continuum. In relation to the waste hierarchy, traditionally the waste treatment options have been limited to landfilling and, in recent decades, incineration.

It is still the case in many countries that landfill constitutes the cheapest waste management option (with the exception of home composting where one considers this as a management option rather than waste minimisation).

On the other hand, the objectives and targets set within the proposed EU Circular Economy Package will provide varying degrees of challenge to Member States [117]. Table 8 shows in details actual performance, based on 2012 data, against targets set for 2030 within the proposed Circular Economy Package. Encouragingly, each of the 2030 performance targets has already been reached by at least one Member State. Additionally, 10 of the Member States have already achieved the 2030 target for paper & cardboard packaging. It can be seen however, that the targets for municipal waste and wood packaging are particularly challenging for many Member States, with over 50 percent of the Member States being more than 20 percent away from the 2030 targets [117].

Table 8. Performance of EU-28 Member States in 2012 against the proposed EU Circular Economy Package 2030 targets

Member State	Municipal solid waste		Packaging materials					
	<10% Landfill	>65% Recycle	Glass >85%	Metallic >85%	Paper & cardboard >85%	Wood >75%	Plastic >55%	Total >75%
Austria	4.2%	59.7%	82.9%	61.4%	84.9%	21.5%	34.7%	65.9%
Belgium	1.0%	56.2%	100.0%	97.3%	89.8%	66.1%	41.5%	80.3%
Bulgaria	69.1%	26.6%	60.5%	75.6%	94.2%	53.1%	40.7%	66.5%
Croatia	82.6%	15.1%	62.8%	12.5%	96.1%	0.4%	45.4%	59.7%
Cyprus	79.4%	22.1%	32.4%	98.7%	88.9%	6.2%	44.8%	55.3%
Czech Republic	56.5%	23.2%	81.1%	69.2%	85.9%	25.7%	58.2%	69.9%
Denmark	2.1%	41.0%	80.6%	51.8%	76.5%	40.4%	29.4%	60.1%
Estonia	34.8%	28.7%	70.7%	65.3%	77.2%	59.7%	29.8%	61.3%
Finland	32.9%	33.3%	77.6%	85.3%	99.2%	16.9%	25.4%	59.3%
France	26.7%	37.8%	73.5%	73.9%	91.8%	28.6%	25.1%	64.9%
Germany	0.2%	65.2%	84.7%	92.3%	87.6%	30.3%	49.5%	71.3%
Greece	80.7%	19.3%	54.7%	38.2%	83.6%	41.8%	32.2%	58.6%
Hungary	65.4%	25.5%	34.2%	80.8%	73.0%	18.1%	27.8%	48.5%
Ireland	38.2%	40.4%	85.5%	75.8%	83.0%	82.3%	40.4%	74.0%
Italy	39.1%	40.0%	70.9%	73.6%	84.5%	54.2%	37.5%	66.6%
Latvia	84.2%	15.8%	55.1%	57.8%	75.3%	36.7%	24.0%	51.1%
Lithuania	73.0%	24.3%	72.2%	67.2%	82.4%	48.8%	38.9%	62.2%
Luxembourg	17.6%	47.4%	94.6%	82.4%	76.7%	23.4%	36.7%	62.5%
Malta	82.2%	12.8%	21.3%	41.5%	77.2%	0.8%	32.8%	46.6%
Netherlands	1.5%	49.4%	71.3%	90.7%	88.9%	29.3%	47.7%	69.3%
Poland	59.2%	24.8%	51.2%	46.9%	53.1%	28.5%	22.2%	41.4%
Portugal	54.4%	26.1%	59.6%	72.3%	66.1%	69.7%	30.4%	56.9%
Romania	67.9%	17.5%	66.3%	55.5%	69.8%	41.1%	51.3%	56.8%
Slovakia	73.1%	13.8%	69.4%	67.8%	84.7%	36.7%	57.0%	68.1%
Slovenia	42.5%	48.8%	87.3%	41.6%	78.7%	33.1%	64.8%	66.9%
Spain	60.6%	29.8%	64.2%	78.0%	77.8%	57.9%	35.1%	65.5%
Sweden	0.6%	47.2%	88.2%	74.4%	76.8%	17.2%	34.9%	56.9%
UK	37.1%	43.3%	67.8%	52.1%	86.5%	51.3%	25.2%	61.4%
EU-28	31.7%	42.6%	72.2%	72.3%	83.9%	37.9%	35.5%	64.5%

## 5.2 NON-HAZARDOUS LANDFILL

The EU Landfill Directive represents the most significant piece of European legislation in relation to municipal waste. The requirement for Member States to set up national strategies to reduce the amount of biodegradable municipal waste going to landfill to tackle the high levels of methane gas being discharged to atmosphere from landfills was noteworthy in this respect. Targets for 5-, 8- and 15-year timeframes were set. Member States were given flexibility in how to achieve these targets. Many of the EU-28 MS introduced a landfill tax as a means of diverting waste from landfill, to meet the requirements of the Landfill Directive, with a few Member States implementing a landfill ban. Considerable variation exists in the value of landfill tax between Member States. Figure 35 shows the correlation between landfill tax and landfilling, with a clear pattern of high levels of landfill corresponding to low landfill tax [118].

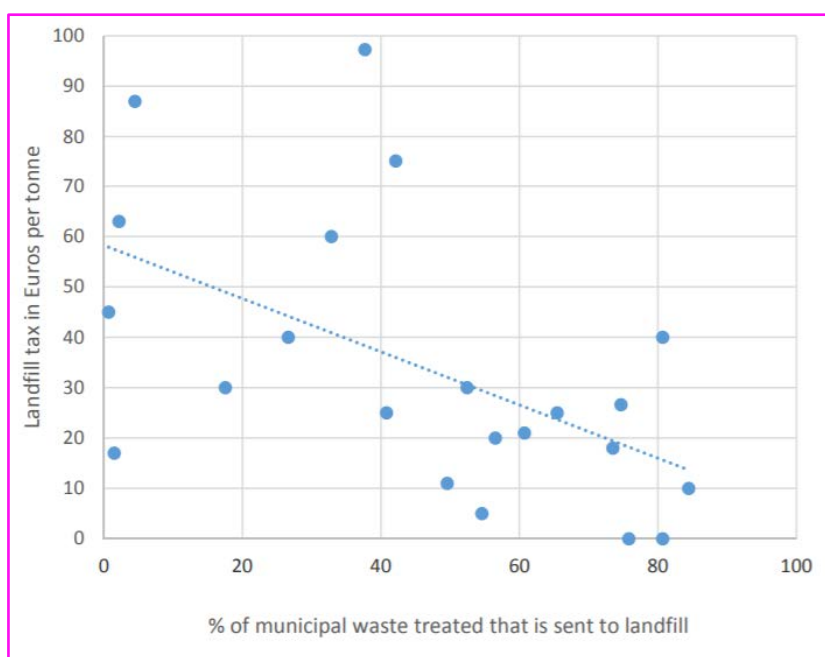


Figure 35: A comparison of landfill gate fees and tax across EU Member States (Source: EEA, 2013)

Actually, the UK gate fees have overall seen a slight decrease to £20/tonne (exclusive of landfill tax). However, variability across the UK is increasing with a range of £2 to £82/tonne. Landfill gate fees vary regionally, depending upon the availability of capacity locally and of alternative options such as EfW or ports for RDF export [119].

In UK, an estimated 815kt of plastic was sent to landfill in 2013. Assuming a landfill cost of £100 per tonne (including both landfill tax and gate fee) then the potential savings from diverting material from landfill could amount to almost £82 million.

Local authorities and waste contractors expect to see increases in landfill gate fees in future years as available landfill capacity reduces.

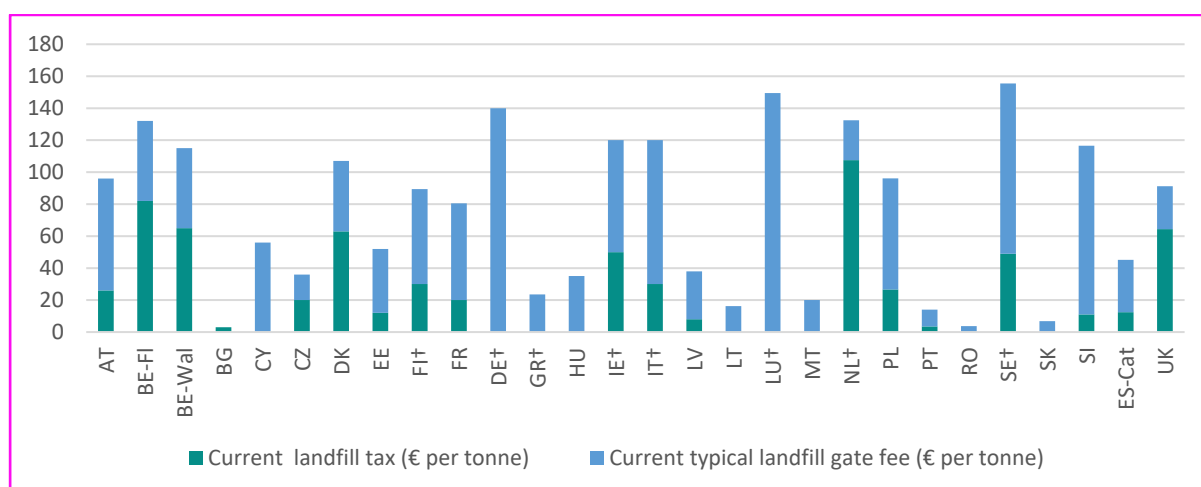


Figure 36. Typical charge (gate fee and landfill tax) for legal landfilling of non-hazardous municipal waste in EU Member States and regions (2013). [118]

In addition, Figure 37 shows the recent gate fees for different waste treatment options in UK in 2019.

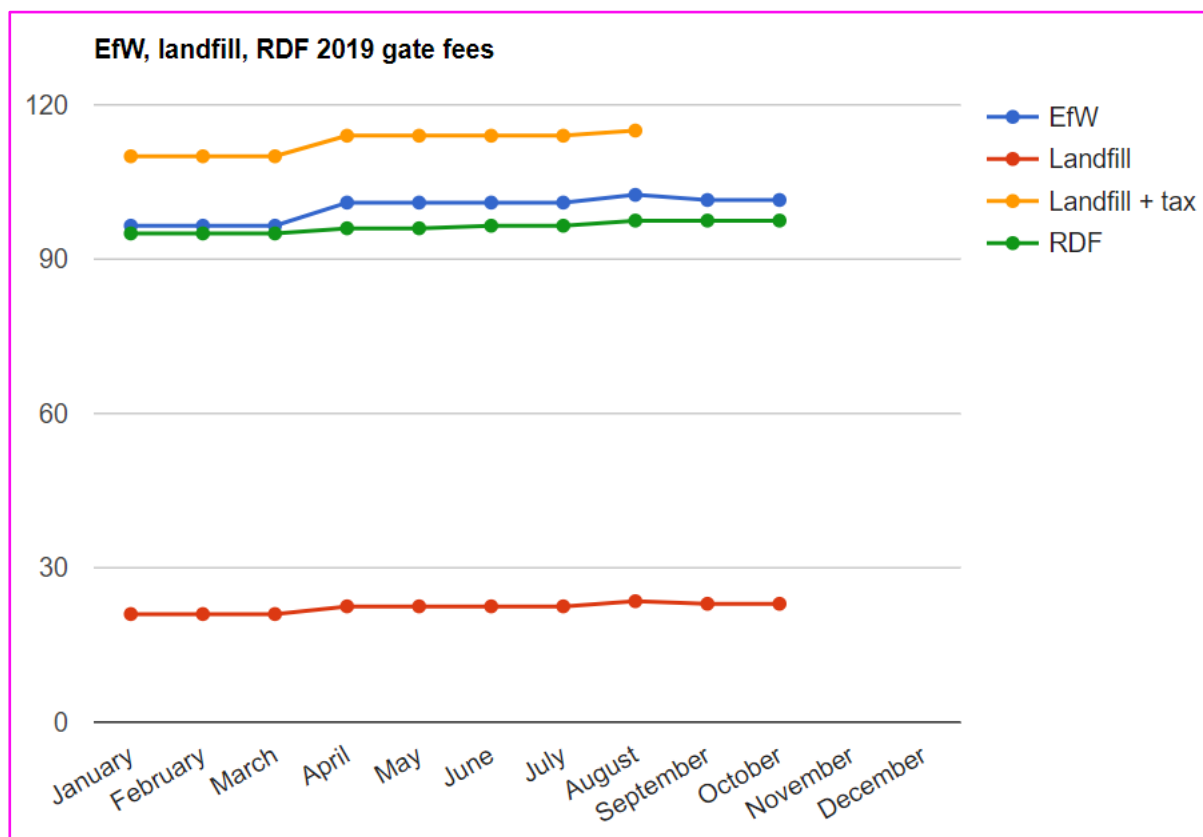


Figure 37. EfW, landfill and RDF gate fees in 2019 (UK) [120]

A criticism of both the landfill tax and a more extreme landfill ban is that waste is often only moved up one level in the waste hierarchy. An example of this can be seen in Figure 36 where nine countries with a landfill ban on plastics are highlighted [121].

Figure 38 shows that on average, the countries with a ban send 32 percent of plastic waste to recovery, 66 percent to incineration and 2 percent to disposal. In comparison, the countries that do not have a ban send, on average, 24 percent plastic waste to recycling, 22 percent to incineration and 54 percent to disposal. The striking finding is that the level of plastic waste recycling is only 8 percent higher in the countries with a ban, whilst the level of incineration is 44 per cent higher than the Member States with no ban. Hence, the outcome of the landfill ban has been primarily to shift plastic waste from landfill to incineration.

## 5.3 MATERIALS RECOVERY FACILITIES

In the UK, the upward trend in MRF gate fees reported in 2016 appears to be continuing. The median MRF gate fee for contracts sorting 4 or more materials is £22/tonne, compared to £15/tonne in 2016. For contracts signed in 2017, the median gate fee is £35/tonne, compared to £29/tonne in 2016.

Several reasons reported for a change in gate fee including signing of a new contract, fee change as result of a regular contractual review, changes in commodity prices, a change in the level of contamination, both



commodity pricing and contamination changes, and an increase in contractual indexation to the retail prices index (RPI).

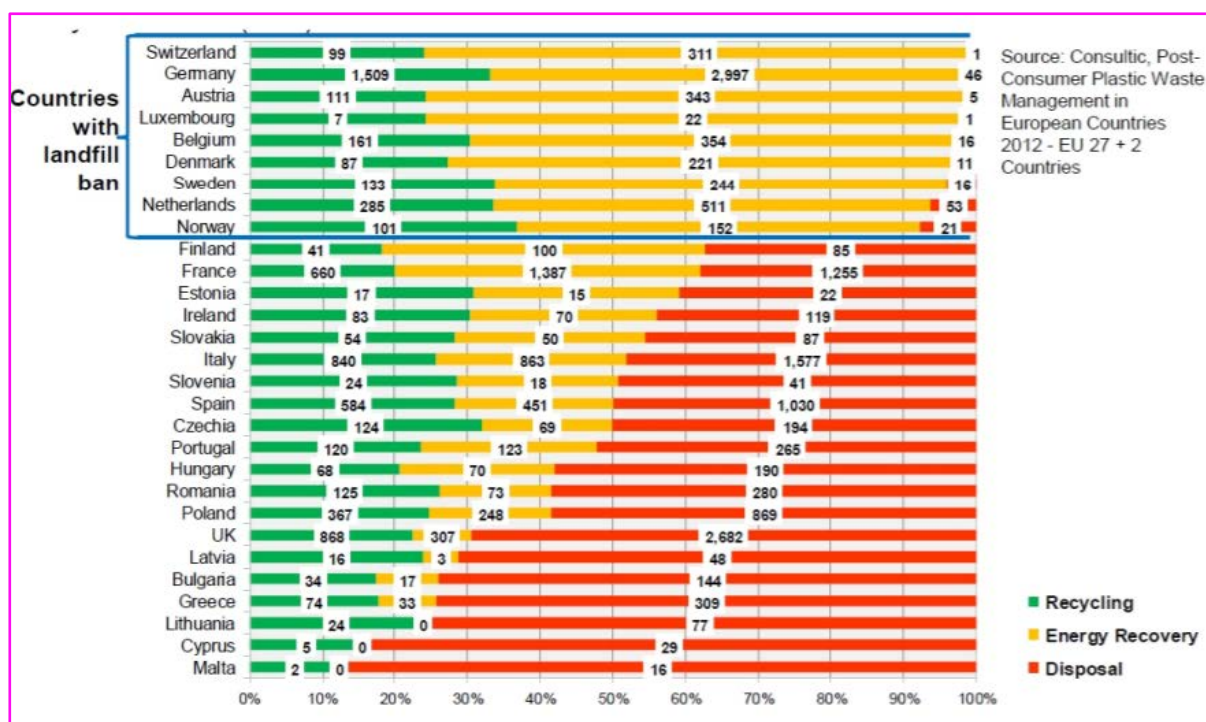


Figure 38: Treatment of plastics waste, comparison of EU-27 (plus Norway and Switzerland) with and without landfill ban (2012)

In addition, the impact of the Chinese restrictions on recycle imports, reflected in commodity price movements and upward pressure on MRF gate fees. Currently, MRF gate fees are £5-10 higher than that at the start of 2018.

When co-mingled materials enter an MRF, larger bulky items such as plastic films and cardboard are removed manually at the pre-sort stage and are either sold or added to the residual waste for disposal [122].

Table 9. Material yielded at pre-sort stage at MRF

Material	Supplied to	(Cost)/Price (£/tonne)*
Large items of plastic film.	Film recycler. In some cases film plastics may be included in the residual stream for disposal	-100 to 150 0 to 30
Cardboard	Paper merchant or mill, or baled for export	116 to 124
Large non-recyclables	Final disposal-landfill or incineration	-100

\* Prices are averaged from figures published by letsrecycle.com in 2011; negative figure represents a cost.

The material then passes through a series of manual and automated sorting processes to remove other higher value recyclable materials.

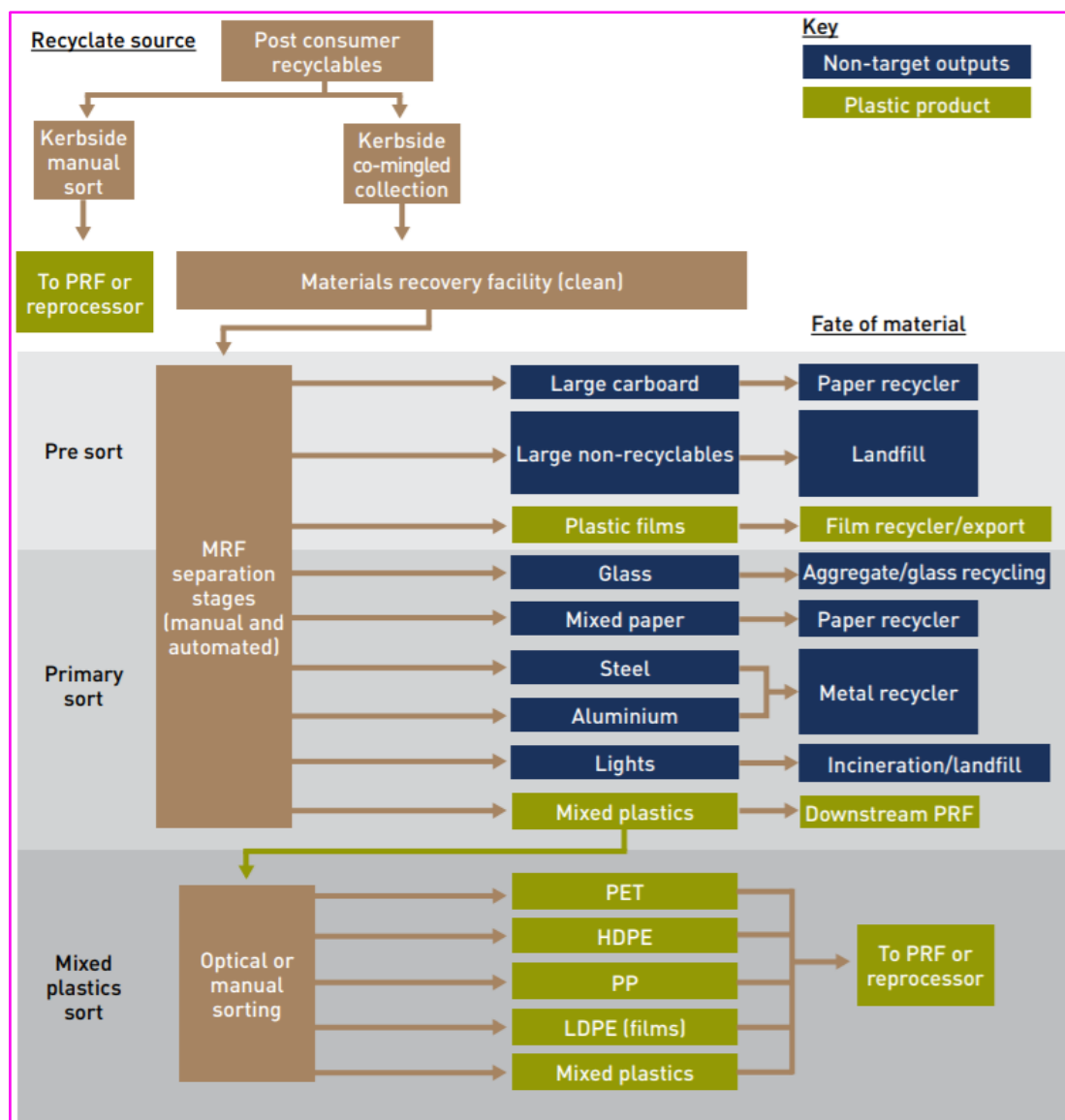


Figure 39. Collection and typical MRF stages of the supply chain [122]

Further sorting and baling can be performed at Plastics Recovery Facilities (PRFs). PRFs are complex plastic sorting facilities with high capital costs because they need automated separators to produce a range of different polymer types.

PRFs typically employ both manual and optical sorting processes to sort plastics by polymer type. The optical sorters used in PRFs sort only by polymer type, they do not distinguish between bottles and non-bottle rigid packaging of the same polymer type. PRFs generally separate out PET, HDPE, PP and PS, and then separate these further into coloured and clear streams, as clear plastics bring a higher value [122].

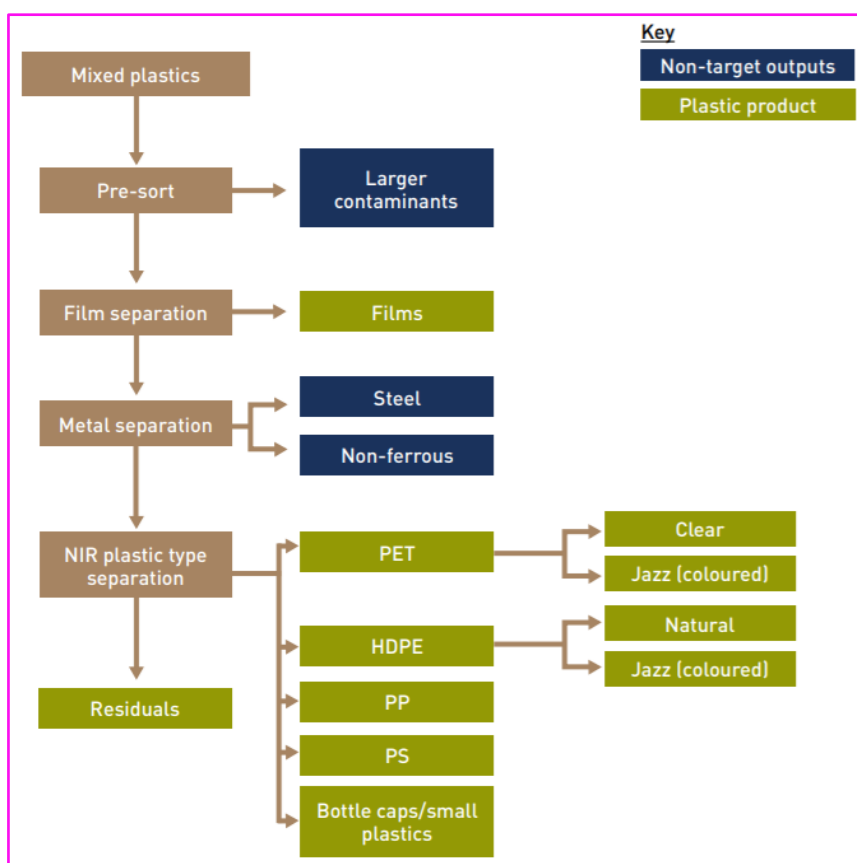


Figure 40. An example PRF process flow diagram [122]

Recovered plastic prices depend upon their demand, i.e. applications sector, market size and quality of recovered plastics with regard to virgin polymers. Prices are also determined by their supply, i.e. are they available to a high and consistent quality?

The plastics collected by Local Authorities and commercial organisations typically have established end markets and so their price reflects this. There are always costs associated to extracting plastics from certain streams and/or converting plastics recovered from the residual stream into a feedstock that can be used. Nevertheless, being able to access waste plastics currently going to residual disposal routes is likely to increase their value.

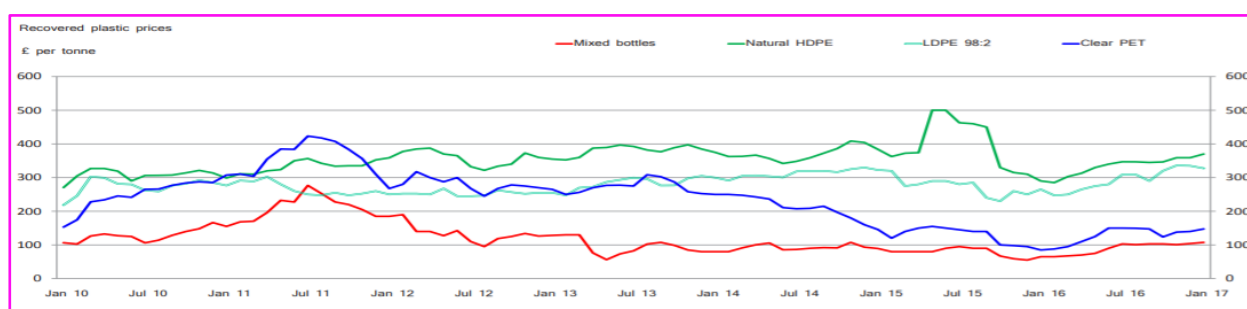


Figure 41. The price trend of recovered plastics between 2010 and 2017 in UK [120]

Table 10. Comparison of recovered plastics prices in 2017 and 2019 [120]

Material	2017	2019
Clear PET	130-165	222.5
Coloured PET	40-55	50
Natural HDPE	360-380	490
Mixed HDPE	170-250	385
Mixed bottles	95-120	
LDPE 98:2 film	300-355	275
Mixed rigids	0-40	
Carrier bags (baled)	15-30	
PP	230	
PS	125	

**Clear PET** - Bottles made out of clear Polyethylene Terephthalate; SPI Polymer identification number 1. Bottle Description: Fizzy drinks, clear mineral water bottles with a blue tint, squashes, cooking oil Exclusions: Strong coloured PET (e.g. green, dark blue and brown); other polymer types

**Coloured PET** - Bottles made out of Polyethylene Terephthalate which are coloured; SPI Polymer identification number 1. Bottle Description: Light green, dark green, dark blue, red, silver, any other colours. Exclusions: Brown PET; other polymer types **Mixed polymer** – Refers to a mixture of PET and HDPE bottles; SPI Polymer identification numbers 1-7 Bottle Description: All polymer types of plastic bottles mixed together, brown bottles The proportion of different polymers in a tonne of mixed polymer bottles and the level of contamination can have a significant impact on the price. As such the prices quoted in the MPR may not be reflective of every deal done in the market at any one time.

**Natural HDPE** - Bottles made out of clear High Density Polyethylene; SPI Polymer identification number 2.

**Mixed HDPE** - Bottles made out of a mixture of clear and coloured High Density Polyethylene; SPI Polymer identification number 2 Bottle Description: Milk bottles, non coloured fresh fruit juice mixed with dark washing up liquid, detergents, fabric conditioners, bleach and household cleaning fluids, hair care, bath and shower bottles. Exclusions: Other polymer types

**LDPE 98/2** - Film made out of Low Density Polyethylene; SPI Polymer identification number 4. The 98/2 film grade should consist of a minimum 98% clear LDPE packaging film. A maximum of 2% coloured LDPE film is allowed within the grade. The baled material should be supplied clean, dry and free of any odour.

**Mixed rigids** – A mixture of household products, including pots, tubs and trays but excluding bottles and film.

**Carrier bags** - refer to the common household degradable plastic bags sourced from supermarkets. They are made out of polyethylene (PE) and a small amount of colouring. Not to be confused with bio-degradable bags. The prices included in the report will refer to their baled format.

## 5.4 ENERGY FROM WASTE FACILITIES

Figure 42 provides a breakdown of the municipal waste sent to incineration in the EU-28. This shows that Denmark, Sweden, Netherlands, Belgium and France each incinerate over 35% of municipal waste and need to switch from incineration to hit the 65% recycling target. Figure 42 also shows that 16.7 per cent of municipal waste in Germany was incinerated without energy recovery, accounting for 8.3 million of the 9 million tonnes treated in this way across the whole of the EU-28. However, the EEA (2013b) reports that this does not necessarily reflect the actual amount of municipal waste incinerated since it is reported to include ‘treatment for disposal’, mostly referring to waste that has already undergone mechanical biological treatment.

Current plans will see an increase in incineration in some countries. Poland is investing heavily in building EfW/CHP infrastructure in many of its cities to reduce its dependency on both landfilling of waste (currently over 59 per cent of municipal waste is landfilled) and importation of energy and fuel. England is in a similar position to Poland, with the Waste Infrastructure Delivery Programme (WIDP) funding an increase in EfW capacity of over 5 million tonnes between 2013 and 2020.

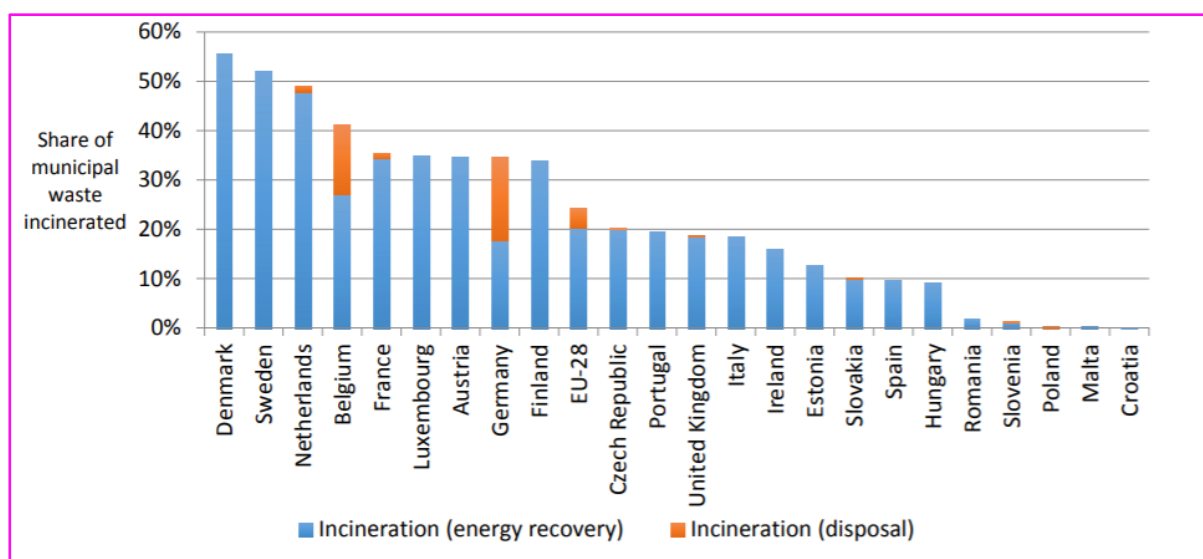


Figure 42: The percentage of municipal waste incinerated in EU-28 in 2012 (Eurostat, accessed June 2017) [117]

In 2017, the UK's reported median gate fee for incineration with energy recovery (EfW) was £86/tonne compared to £83/tonne in 2016. The study performed by WRAP indicates that for pre-2000 EfW facilities, the median gate fee in 2017 was £57/tonne, compared to £56/tonne a year before. For post-2000 facilities, median gate fee was £89/tonne compared to £91/tonne in 2016. Three authorities reported new contracts in 2017 for post-2000 facilities with a median gate fee of £91/tonne. Commercial prices of £90-£100/tonne are reported, depending upon the local competitive position [119].

Cement plants burn mixed plastics with the prices from 15-35 €/t. The material should be shredded on dimension between 20-30 mm. Cement plants have also second dosing line where big size waste can be fed in. Dimensions here are up to 60-80 mm and prices are also different and ranges from 80 to 120 €/t.

## 5.5 SPECIFIC CASES

### 5.5.1 End of Life mattresses

Several companies in France, The Netherlands, U.K. and Germany operate so-called mattress recycling units which in reality are limited for 90 % + to collection and dismantling.

The actual process of mattress recycling generally involves processing waste mattresses into constituent materials and supplying these materials on to relevant end markets. The composition of mattresses varies greatly, but they are usually categorised based on their main core material, which fall into three common types; steel springs, polyurethane foam, and latex foam. Mattresses may also contain other shell materials surrounding the core, and tick which contain and protect the internal sections of the mattress, see Figure 43. Different material types are separated to achieve maximum value in end markets, therefore motivating the need to disassemble and isolate materials types.

This separation of materials forms the core activity for mattress recycling, as sales of materials such as steel from springs and textiles from filling materials is a key source of income. In general, this process is carried

out by hand because the variability in construction, design and materials, makes the process difficult to automate effectively [123].

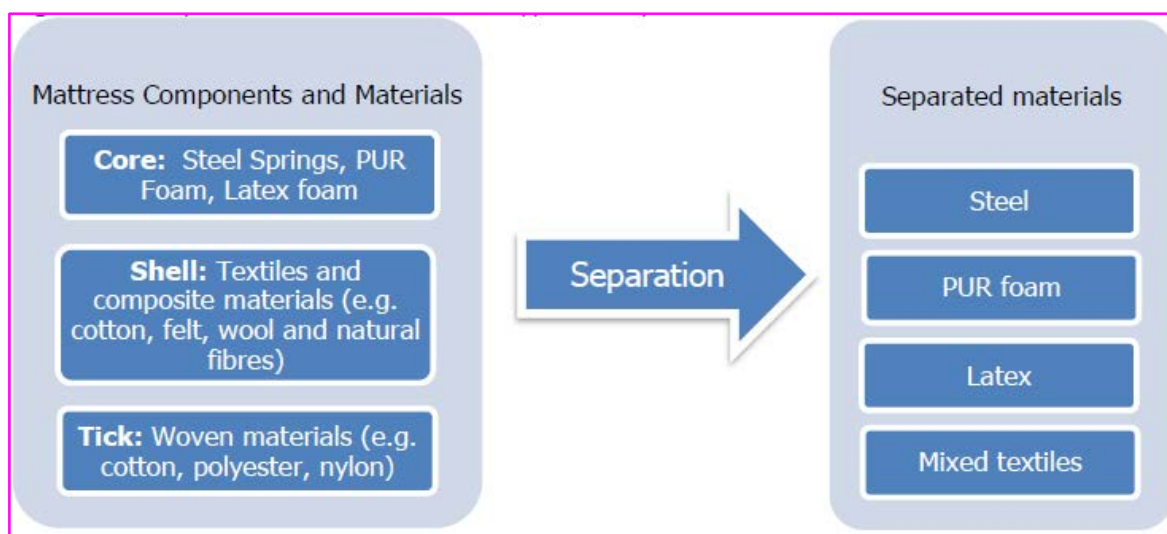


Figure 43. Composition of mattresses and types of separated materials [123]

The average composition of a mattress is shown in Table 11. The main contributors to the weight are steel and PUR foam: 29% and 25% respectively. In practice textiles are grouped together, as they are difficult to separate due to the construction of the mattress, and are therefore sold on to mixed textiles markets. 'Mixed textiles' accounts for 7.7kg or 36% of the mattress weight. Natural fibres, which include coconut fibres, sisal, jute, and hemp, are estimated to account for 1.6kg or 7.5% of the weight and are often included in the mixed textiles.

Table 11. Average mattress material composition

Material	Average mattress composition (kg)	Average mattress composition (%)
Steel	6.2	29%
PUR foam	5.3	25%
Cotton, non-woven	3.3	15%
Natural Fibres (e.g. coconut, sisal, jute)	1.6	7%
Felt	1.6	7%
Cotton, woven	1.4	6%
Wool	0.8	4%
Polyester, non-woven	0.8	4%
Latex foam	0.6	3%
<b>Total</b>	<b>21.4</b>	<b>100%</b>

Landfill remains a cheap option for councils and other waste handlers; a typical mattress weighing 21.4kg would cost £1.75 to dispose of via landfill in 2012, rising to an estimated £1.93 and £2.10 in 2013 and 2014 based in rises in landfill tax. This often limits the up-front gate fee that organisations are willing to pay to mattress recyclers despite the clear benefits over landfill, although others would pay more due to the environmental benefits. Some organisations will extract value from mattress materials as part of general

waste handling, typically by shredding which allows the reclamation of steel. However, it is vital for the viability of the mattress recycling business to increase the gate fee above the landfill costs because of the additional environmental benefits which may be gained.

Polyurethane recycling is a commitment to the circular economy with which the life cycle of waste is closed by converting it into new raw materials with which to manufacture products. Furthermore, with the recycling process, the quality and properties are preserved, giving rise to raw materials with the same features as the original ones.

Currently, three markets exist for separated PUR foam: recycling, energy from waste (EfW) and landfill cover (as part of mixed shredded materials). Recycling offers the highest value of these options, with markets varying depending on the source, quality and intended use. PUR foam from mattresses is typically used for re-bonding, with small pieces bound under pressure to form products such as carpet underlay or gym mats. A value of around £100 per tonne when collected was identified for post-consumer scrap. However, factors such as location and customer perception (particularly about hygiene) potentially limit the scale of this market [124].

To increase the recycling of mattresses few initiatives has recently been launched. Through its RENUVA™ Mattress Recycling Program, Dow aims to reduce the waste by giving PU foam from end-of-life mattresses a new life and enable a circular economy for polyurethanes. The programme will take discarded mattress foam and turn it back into raw material, i.e. RENUVA™ polyols, through chemical recycling, the process of converting waste into feedstock. The recovered RENUVA™ polyol can be used in flexible or rigid foam products which replace virgin polyol. This can go into applications such as building insulation boards and even back into new mattresses. At capacity, the first plant in France will recycle PU foam from up to 200,000 mattresses annually. Unlike the incineration process currently used, the chemical recycling adopted by the RENUVA™ Programme contributes towards approximately 30% lower CO<sub>2</sub> emissions, according to an internal Life Cycle Assessment. As such, landfills are reduced, incineration avoided, and the industry's carbon footprint improved [125].

With the circular economy concept BASF aims to offer a solution to finally closing the loop for polyurethane soft foam with the chemical recycling of mattresses. BASF's process breaks down the flexible polyurethane and delivers the initially used polyol. From there BASF can produce new foam with a significantly lower carbon footprint, because fewer fossil resources are used [126].

The two other markets offer lower value alternatives. Foam can be sent to EfW processing or resource derived fuel (RDF), with an estimated value of £34 per tonne. Alternatively, it can be shredded, mixed with other materials and used as landfill cover, which is cost neutral as it avoids the cost of landfill.

### 5.5.2 End of Life carpets

Table 12 shows the estimated breakdown of the post-consumer waste carpet mix. The type of carpet influences the various methods of recycling due to the outlets for the products produced. Synthetic carpets typically are recycled for equestrian surfaces and polypropylene recovery, whereas wool carpet may be recycled for non-woven products or compost and growing media [124].

**Table 12: Post-consumer waste carpet mix, 2010**

Material	Average carpet composition (%)
----------	--------------------------------



Mixed synthetic – nylon, polypropylene & polyester	60
Wool rich	26
Nylon & bitumen based carpet tiles	14
Total	100%

In most cases, the gate fee cost itself is not a limiting factor. However, as a component of the overall cost it is an important feature, particularly in its conversion to cost per tonne, which is required to compare to the current cost of disposal.

In order for carpet reprocessors to be economically sustainable, they are reliant on their outputs being of the highest quality possible. For this reason, some reprocessors have a specification of the types and/or condition of the carpets that they will accept, depending on the type of reprocessing they carry out, and often they will have a limit on the amount of acceptable contamination. For example, if they produce very specific product outputs then they are likely to have a more demanding specification, compared to those who send a large proportion of material to EfW. Therefore, carpet reprocessors charge a gate fee per tonne of carpet, which has ranged between £50 and £80 per tonne (March 2014), depending on the specification requirements [124].



## 6 CONCLUSIONS / CONTRIBUTION TO THE SPIRE ROADMAP

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Sustainability is ever more relevant in today's society and plastics waste is at the forefront of many debates and discussions around the drive towards a more circular economy. The way plastics are currently produced, used and disposed fails to capture the economic benefits of a more 'circular' approach and harms the environment.

Fortunately, a range of policies and measures are already in place or in the phase of development in Europe that support the transition to a circular economy for plastics, such as EU Green Deal, New Circular Economy Action Plan, Chemicals Strategy for Sustainability, Circular Plastics Alliance and Packaging and Packaging Waste Directive.

To achieve circular plastics economy, recyclable plastic waste would have to be gradually phased out from landfilling and incineration for energy production. This would be a great challenge, in particular as incineration plants contribute significantly to the heating needs of municipalities.

However, prohibiting the landfilling and incineration of recyclable plastic waste would lift one of the major barriers of plastic recycling, the supply of waste plastic. It could provide a large quantity of waste of variable quality. Therefore, a ban on landfill or reducing incineration would necessarily need complementary measures of sorting and recycling technology development, as well as capacity expansion. In order to shape a future with higher recycling rates and more efficient recycling procedures, innovative techniques and methods have to be established.

The results of this project, together with the identified barriers in the EU market of plastic waste, can form the basis of future research on the appropriate policy measures required to increase plastic recycling in Europe. Policy instruments need to be thoroughly analysed and evaluated in order to provide potential solutions and policy tools that will enable the transition to a low carbon circular economy in Europe.

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## BIBLIOGRAPHY / REFERENCES

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- [1] PlasticsEurope report. Plastics – The Facts 2018.
- [2] N. V. Gama, A. Ferreira, A. Barros-Timmons. *Materials* 2018, 11, 1841.
- [3] M. Ionescu. *Chemistry and Technology of Polyols for Polyurethanes*; Rapra Technology Limited: Shawbury, UK, 2005; ISBN 1859574912.
- [4] Polyurethane Global Market Size Forecast 2021. Available online: <https://www.statista.com/statistics/720449/global-polyurethane-market-size-forecast/> (accessed on 16 May 2019).
- [5] E. Palm, E. Svensson Myrin. *Mapping the Plastics System and Its Sustainability Challenges*; Lund University: Lund, Sweden, 2018; p. 37.
- [6] IAL Consultants. New Market Study. <https://www.gupta-verlag.com/news/industry/22577/new-market-study-from-ial-consultants-polyurethane-chemicals-and-products-in-emea-2018.print> (accessed on 14 April 2019)
- [7] (a) IAL Consultants. The 12th Edition of Report on the Markets for Polyurethane Chemicals and Products in Europe, Middle East and Africa; IAL Consultants: Ealing, UK, 2018; (b) Polyurethane Production, Pricing and Market Demand. Available online: <https://www.plasticsinsight.com/resin-intelligence/resin-prices/polyurethane/> (accessed on 16 May 2019).
- [8] (a) Mordor Intelligence report. <https://www.mordorintelligence.com/industry-reports/europe-polyurethanes-market-industry> (accessed on 2 June 2019); (b) IAL Consultants. The 13th Edition of Report on the Markets for Polyurethane Chemicals and Products in Europe, Middle East and Africa; IAL Consultants: Ealing, UK, 2020.
- [9] M. Szycher, *Szycher's Handbook of Polyurethanes*, 2nd ed.; CRC Press: New York, NY, USA, 2006.
- [10] K. Ashida. *Polyurethane and Related Foams Chemistry and Technology*; Taylor & Francis Group: Boca Raton, FL, USA, 2007.
- [11] IAL Consultants report. [http://www.ialconsultants.com/uploads/CUBE\\_press\\_release/2018-09-10/polyurethane\\_EMEA\\_press\\_release\\_18\\_KTedit.pdf](http://www.ialconsultants.com/uploads/CUBE_press_release/2018-09-10/polyurethane_EMEA_press_release_18_KTedit.pdf)
- [12] <http://www.essentialchemicalindustry.org/polymers/polyurethane.html> (accessed on 13 April 2019)
- [13] J. O. Akindoyo et. al. *RSC Advances* 2016, 6, 114453.
- [14] P. Cinelli, I. Anguillesi and A. Lazzeri, Green synthesis of flexible polyurethane foams from liquefied lignin, *Eur. Polym. J.*, 2013, 49, 1174–1184.
- [15] P. Singhal, W. Small, E. Cosgriff-Hernandez, D. J. Maitland and T. S. Wilson, Low density biodegradable shape memory polyurethane foams for embolic biomedical applications, *Acta Biomater.* 2014, 10, 67.
- [16] R. Hodlur and M. Rabinal, Self-assembled graphene layers on polyurethane foam as a highly pressure sensitive conducting composite, *Compos. Sci. Technol.* 2014, 90, 160.
- [17] S. Kang, S. Kwon, J. Park and B. Kim, Carbon nanotube reinforced shape memory polyurethane foam. *Polym. Bull.* 2013, 70, 885.
- [18] H. D. Liu, Z. Y. Liu, M. B. Yang and Q. He, Surperhydrophobic polyurethane foam modified by graphene oxide. *J. Appl. Polym. Sci.* 2013, 130, 3530.
- [19] M. M. Alavi Nikje. *Recycling of Polyurethane Waste*, 2nd ed, De Gruyter: Boston, USA, 2019.
- [20] European Flexible Packaging Association (Europur) internal report.
- [21] Z. S. Petrović, X. Wan, O. Bilić, A. Zlatanić, J. Hong and I. Javni, Polyols and polyurethanes from crude algal oil. *J. Am. Oil Chem. Soc.* 2013, 90, 1073.

- [22] S. D. Rajput, D. G. Hundiware, P. P. Mahulikar and V. V. Gite, Fatty acids based transparent polyurethane films and coatings. *Prog. Org. Coat.* 2014, 77, 1360.
- [23] M. Szycher, Basic concepts in polyurethane chemistry and technology. Szycher's handbook of polyurethanes, CRC Press, Taylor & Francis, Boca Raton, FL, 1999.
- [24] Y. Xu, Z. Petrovic, S. Das and G. L. Wilkes, Morphology and properties of thermoplastic polyurethanes with dangling chains in ricinoleate-based soft segments. *Polymer* 2008, 49, 4248.
- [25] D. Rosu, L. Rosu and C. N. Cascaval, IR-change and yellowing of polyurethane as a result of UV irradiation, *Polym. Degrad. Stab.* 2009, 94, 591.
- [26] P. Davies and G. Evrard, Accelerated ageing of polyurethanes for marine applications, *Polym. Degrad. Stab.* 2007, 92, 1455.
- [27] X. F. Yang, J. Li, S. Croll, D. Tallman and G. Bierwagen, Degradation of low gloss polyurethane aircraft coatings under UV and prohesion alternating exposures, *Polym. Degrad. Stab.* 2003, 80, 51.
- [28] V. Gite, P. Mahulikar and D. Hundiware, Preparation and properties of polyurethane coatings based on acrylic polyols and trimer of isophorone diisocyanate, *Prog. Org. Coat.* 2010, 68, 307.
- [29] 15 D. Chattopadhyay and D. C. Webster, Thermal stability and flame retardancy of polyurethanes, *Prog. Polym. Sci.* 2009, 34, 1068.
- [30] 23 K. M. Zia, H. N. Bhatti and I. A. Bhatti, Methods for polyurethane and polyurethane composites, recycling and recovery: A review, *React. Funct. Polym.* 2007, 67, 675.
- [31] Q. Jing, Q. Liu, L. Li, Z. Dong and V. V. Silberschmidt, Effect of graphene-oxide enhancement on large-deflection bending performance of thermoplastic polyurethane elastomer, *Composites, Part B* 2016, 89, 1.
- [32] S. Liu, H. Sun, N. Ning, L. Zhang, M. Tian, W. Zhu and T. W. Chan. Aligned carbon nanotubes stabilized liquid phase exfoliated graphene hybrid and their polyurethane dielectric elastomers, *Compos. Sci. Technol.* 2016, 125, 30.
- [33] S. A. Madbouly, Y. Xia and M. R. Kessler, Rheological behavior of environmentally friendly castor oil-based waterborne polyurethane dispersions, *Macromolecules* 2013, 46, 4606.
- [34] S. A. Madbouly and J. U. Otaigbe, Kinetic analysis of fractal gel formation in waterborne polyurethane dispersions undergoing high deformation flows, *Macromolecules* 2006, 39, 4144.
- [35] L. Lei, L. Zhong, X. Lin, Y. Li and Z. Xia, Synthesis and characterization of waterborne polyurethane dispersions with different chain extenders for potential application in waterborne ink, *Chem. Eng. J.* 2014, 253, 518.
- [36] L. Lei, Z. Xia, C. Ou, L. Zhang and L. Zhong, Effects of crosslinking on adhesion behavior of waterborne polyurethane ink binder, *Prog. Org. Coat.*, 2015, 88, 155–163.
- [37] A. Serrano, A. M. Borreguero, I. Garrido, J. F. Rodriguez and M. Carmona. Reducing heat loss through the building envelope by using polyurethane foams containing thermoregulating microcapsules, *Appl. Therm. Eng.*, 2016, 103, 226.
- [38] <https://polyurethane.americanchemistry.com/Applications/>
- [39] J. Njuguna, S. Michałowski, K. Pielichowski, K. Kayvantash and A. C. Walton, Fabrication, characterization and lowvelocity impact testing of hybrid sandwich composites with polyurethane/layered silicate foam cores, *Polym. Compos.*, 2011, 32, 6.
- [40] R. Deng, P. Davies and A. Bajaj. *J. Sound Vib.* 2003, 262, 391.
- [41] N. M. Zain, E. N. Roslin and S. Ahmad, Preliminary study on bio-based polyurethane adhesive/aluminum laminated composites for automotive applications, *Int. J. Adhes. Adhes.* 2016, 71, 1.

- [42] P. Xiao, Y. Dudal, P. F. X. Corvini, U. Pieleles and P. Shahgaldian, Cyclodextrin-based polyurethanes act as selective molecular recognition materials of active pharmaceutical ingredients (APIs), *Polym. Chem.* 2011, 2, 1264.
- [43] P. Davies and G. Evrard, Accelerated ageing of polyurethanes for marine applications, *Polym. Degrad. Stab.*, 2007, 92, 1455.
- [44] S. Dutta and N. Karak, Synthesis, characterization of poly(urethane amide) resins from Nahar seed oil for surface coating applications, *Prog. Org. Coat.*, 2005, 53, 147.
- [45] S. Dutta, N. Karak and T. Jana, Evaluation of Mesua ferrea L. seed oil modified polyurethane paints, *Prog. Org. Coat.*, 2009, 65, 131.
- [46] R. A. Van Benthem, Novel hyperbranched resins for coating applications, *Prog. Org. Coat.*, 2000, 40, 203.
- [47] 239 J. Yi, C. Huang, H. Zhuang, H. Gong, C. Zhang and R. Ren, Degradable polyurethane based on star-shaped polyester polyols (trimethylolpropane and 3-caprolactone) for marine antifouling, *Prog. Org. Coat.*, 2015, 87, 161.
- [48] B. Zhou, Y. Hu, J. Li and B. Li, Chitosan/phosvitin antibacterial films fabricated via layer-by-layer deposition, *Int. J. Biol. Macromol.* 2014, 64, 402.
- [49] Polyurethanes and medical applications. <https://polyurethane.americanchemistry.com/Polyurethanes-and-Medical-Applications/>
- [50] M. Garrido, J. R. Correia and T. Keller, Effect of service temperature on the shear creep response of rigid polyurethane foam used in composite sandwich floor panels, *Construct. Build. Mater.*, 2016, 118, 235.
- [51] M. A. Mekewi, A. M. Ramadan, F. M. ElDarse, M. H. A. Rehim, N. A. Mosa and M. A. Ibrahim, Preparation and characterization of polyurethane plasticizer for flexible packaging applications: Natural oils affirmed access, *Egypt. J. Pet.*, 2016, DOI: 10.1016/j.ejpe.2016.02.002.
- [52] ISOPA report. Socio-economic contribution of the polyurethane industry to growth and jobs in Europe.
- [53] J E McIntyre. Synthetic fibres, nylon, polyester, acrylic and polyolefin. CRC Press, FL, USA, 2005.
- [54] L Mascia. Polymers in Industry from A to Z. WILEY-VCH, Weinheim, Germany, 2012.
- [55] J-Y. Lee, K-J. Kim. Elastomers and Composites 2016, 51, 317.
- [56] CMAI report.
- [57] (a) <https://www.icis.com/explore/resources/news/2020/07/31/10536228/europe-capro-nylon-demand-slowly-picks-up-but-uncertainty-prevails> (accessed on 21 December 2020); (b) M. Gilbert. Aliphatic polyamides. In: Brydson's Plastics Materials. 8th ed, ELSEVIER, Oxford, UK, 2017.
- [58] (a) Arkema internal report, 2012; (b) <https://www.hdinresearch.com/> (accessed on 15 December 2020).
- [59] Polyamide properties, production, price, market and uses. <https://www.plasticsinsight.com/resin-intelligence/resin-prices/polyamide/> (accessed on 5 July 2019).
- [60] PA6/PA66 – Properties, experiences and useful links. <https://www.plasticprop.com/articles/pa6pa66-properties-experiences-and-useful-links> (accessed on 29 April 2019).
- [61] Polyamide market by type – PA6. <https://www.marketindustryreports.com/> (accessed on 3 January 2021).
- [62] M. Scheibitz, R. Kaneko, P. Spies. Polyamid 6 and 66 (PA6 and PA66). *Kunststoffe international* 10/2016.
- [63] MarketWatch. <https://www.marketwatch.com/press-release/polyamide-pa-market-share-size-2019-global-trends-comprehensive-research-study-development-status-opportunities-future-plans-competitive-landscape-and-growth-by-forecast-2024-2019-08-02> (accessed on 5 August 2019).



- [64] MarketWatch. [https://www.marketwatch.com/press-release/europe-is-expected-to-drive-the-demand-and-positively-impact-specialty-polyamides-market-growth-over-the-forecast-period-2019-05-10-131972250?mod=mw\\_quote\\_news](https://www.marketwatch.com/press-release/europe-is-expected-to-drive-the-demand-and-positively-impact-specialty-polyamides-market-growth-over-the-forecast-period-2019-05-10-131972250?mod=mw_quote_news) (accessed on 26 April 2019).
- [65] <http://atozplastics.com/upload/Literature/Polyamide.asp> (accessed on 15 February 2019).
- [66] J. Wesolowski, K. Plachta. The polyamide market. DOI: 10.5604/12303666.1215537.
- [67] Papers from Du Pont Fakuma Fair 2014: Werkstoffentwicklungen und anwendungstechnische Zusammenarbeit als Antrieb für Innovationen.
- [68] Chemical Fiber International 2012, 2, 74.
- [69] KPMG International report: The Plastic Recycling Opportunity.
- [70] JRC technical reports. End-of-waste criteria for waste plastic for conversion.
- [71] R. Geyer, J. R. Jambeck, K. L. Law. Science Advances 2017, 3, e1700782.
- [72] EuPC internal market report, done by AMI.
- [73] ISOPA Fact Sheet. Recycling and recovery of polyurethanes.
- [74] EUROPUR report. Flexible polyurethane foam in mattresses and furniture.
- [75] Textiles – Mattress and bedding waste. <https://www2.mmu.ac.uk/environmental-science-research/waste-to-resource-innovation-network/our-services/innovation-projects/> (accessed on 11 May 2019).
- [76] Erasmus+ Project (2017-1-BE01-KA202-024752) report. CIRCULAR ECONOMY IN THE FURNITURE INDUSTRY: OVERVIEW OF CURRENT CHALLENGES AND COMPETENCES NEEDS.
- [77] JRC Scientific and Technical Reports. Assessment of the environmental advantages and drawbacks of existing and emerging polymers recovery processes.
- [78] PU Europe report. Waste management and polyurethane insulation in the context of resource efficiency.
- [79] Deutsche Umwelthilfe e.V. Report. Swept under the carpet: The big waste problem of the carpet industry in Germany.
- [80] Information Sheet. Carpet Recycling.
- [81] K. Kaiser, M. Schmid, M. Schlummer. Recycling 2018, 3, 1.
- [82] S. Gritzmam. Master thesis. [https://publik.tuwien.ac.at/files/publik\\_272279.pdf](https://publik.tuwien.ac.at/files/publik_272279.pdf).
- [83] Project Report. Plastic waste recovery by regional blockchain networks.
- [84] European Commission. 'A European Plastics Strategy for a Circular Economy'. <http://ec.europa.eu/environment/circular-economy/pdf/plastics-strategybrochure.pdf>. (accessed on 20 January 2019).
- [85] (a) C. Rittmeyer, P. Kaese, J. Vehlow, W. Vilohr. Decomposition of organohalogen compounds in municipal solid waste incineration plants. Part II: Co-combustion of CFC containing polyurethane foams. Chemosphere 1994, 28, 1455–1465; (b) R. Gómez-Rojo, L. Alameda, Á. Rodríguez, V. Calderón, S. Gutiérrez-González. Polymers 2019, 11, 359; (c) M. Paabo, B. C. Levin. A review of the literature on the gaseous products and toxicity generated from the pyrolysis and combustion of rigid polyurethane foams. Fire Mater. 1987, 11, 1–29; (d) M. A. Garrido, A. C. Gerecke, N. Heeb, R. Font, J. A. Conesa. Isocyanate emissions from pyrolysis of mattresses containing polyurethane foam. Chemosphere 2017, 168, 667–675.
- [86] S. Członka, M. F. Bertino, K. Strzelec, A. Strakowska, M. Maślowski. Polymer Testing 2018, 69, 225.
- [87] C. Junco, A. Rodríguez, V. Calderón, C. Muñoz-Rupérez, S. Gutiérrez-González. Fatigue durability test of mortars incorporating polyurethane foam wastes. Constr. Build. Mater. 2018, 190, 373.
- [88] P. Mounanga, W. Gbongbon, P. Poullain, P. Turcry. Proportioning and characterization of lightweight concrete mixtures made with rigid polyurethane foam wastes. Cem. Concr. Compos. 2008, 30, 806.



- [89] M. Kismi, P. Mounanga. Comparison of short and long-term performances of lightweight aggregate mortars made with polyurethane foam waste and expanded polystyrene beads. In Proceedings on 2nd International Seminar on Innovation and Valorization in Civil Engineering and Construction Materials; MATEC Web of Conferences: Paris, France, 2012; Volume 2, p. 02019.
- [90] J. Gadea, A. Rodríguez, P. L. Campos, J. Garabito, V. Calderón. Lightweight mortar made with recycled polyurethane foam. *Cem. Concr. Compos.* 2010, 32, 672.
- [91] (a) M. M. Alavi Nikje, A. Bagheri Garmarudi, A. B. Idris. *Designed Monomers and Polymers* 2011, 14, 395; (b) D. Simón, A. M. Borreguero, A. De Lucas, J. F. Rodríguez. Glycolysis of viscoelastic flexible polyurethane foam wastes. *Polym. Degrad. Stab.* 2015, 116, 23–35; (c) M. Modesti, F. Simioni, R. Munari, N. Baldoin. Recycling of flexible polyurethane foams with a low aromatic amine content. *React. Funct. Polym.* 1995, 26, 157–165.
- [92] Recycling success story – bonded carpet cushion (accessed on 26 January 2019).
- [93] C-H. Wu, J-K. Li. *Polymer Degradation and Stability* 2002, 75, 413.
- [94] (a) M. Murai, M. Sanou, et. Al. *Journal of Cellular Plastics* 2003, 39, 15; (b) A. Kemoni, M. Piotrowska. *Polymers* 2020, 12, 1752; (c) <https://corporate.dow.com/en-us/science-and-sustainability/2025-goals/renuva-program.html> (accessed on 4<sup>th</sup> of January 2021); (d) <https://www.retourmatras.nl/nederland-wereldleider-in-matrasrecycling/> (accessed on 4<sup>th</sup> of January 2021).
- [95] R. Singh, F. Fraternali, G. Bonazzi, MSJ. Hashmi, R. Kumar, N. Ranjan (2018) Investigations for development of feed stock filament of fused deposition modeling from recycled polyamide. In: Reference Module in Materials Science and Materials Engineering.
- [96] J. Datta, K. Blazek, M. Wloch, R. Bukowski. *Journal of Polymers and the environment.* 2018, 26, 4415.
- [97] J. Lozano-González, T. Rodriguez-Hernandez, E. Gonzalez-De Los Santos, T. Villalpando-Olmos. *J. Appl. Polym. Sci.* 2000, 75, 851.
- [98] T. Calvo-Correas, L. Ugarte, P. Jutrzenka Trzebiatowska, R. Sanzberro, J. Datta, M. Ángeles Corcuera, A. Eceiza. *Polym. Degrad. Stab.* 2017, 144, 411.
- [99] P. Kopczyńska, J. Datta. *Polym. Int.* 2016, 65, 946.
- [100] J. Datta, P. Kopczyńska, D. Simon, J. Rodriguez. *J. Polym. Environ.* 2018, 26, 166.
- [101] F. Pardal, G. Tersac G. *Polym. Degrad. Stab.* 2006, 91, 2809.
- [102] R. McKinney. Ammonolysis of nylon. 1994, US Patent 5302756.
- [103] A. Nemade, D. Mishra, V. Zope. *J. Polym. Environ.* 2011, 19, 110.
- [104] Y. Wang, Y. Zhang. *Polym. Degrad. Stab.* 2014, 110, 312.
- [105] D. Patil, S. Madhamshettiwar. *J. Appl. Chem.* 2014 <https://doi.org/10.1155/2014/286709>
- [106] K. Kim, D. Dhevi, J. Lee, Y. Cho, E. Choe. *Polym. Degrad. Stab.* 2006, 91:1545.
- [107] X. Zhao, L. Zhan, B. Xie, B. Gao B. *Chemosphere* 2018, 207, 742.
- [108] X. Wang, Z. Wang, S. Liang, Y. Jin, B. Lotz. *Appl. Surf. Sci.* 2018, 442, 595.
- [109] G. Kalfas. *Polym. React. Eng.* 1998, 6, 41.
- [110] JRC Science for Policy Report. Revision of the EU green public procurement (GPP) criteria for textile products and services.
- [111] M. Binder, S. Albrecht, C. Marincovic, L. Flanigan, D. McGavis. Life Cycle Assessment of Caprolactam production from Nylon 6 carpet recycling, 2010, [http://www.lbp-gabi.de/refbase/files/49\\_Binder\\_et al2010.pdf](http://www.lbp-gabi.de/refbase/files/49_Binder_et al2010.pdf)

- [112] (a) W. Karasiak, D. Karasiak. Method and Device for Treating Polymers, WO2014072483A1, 2014; (b) Aquafil, The Econyl project, <http://www.aquafil.com/en/sustainability/the-econyl-project> (accessed on 4 May 2019).
- [113] Hyosung, MIPAN Regen product, <http://www.hyosungtn.com/en/about/intro.do> (accessed on 30 January 2019).
- [114] Unifi, REPREVE product line, <https://unifi.com/products/repreve> (accessed on 14 June 2019).
- [115] M. C. Thiry. Everything old is new again – Recycling, recycled and recyclable fibres, 2010, AATCC review, USA.
- [116] M.A.V. De Souza, G.S. Montenegro, K. Faceli, V. Casadei. Waste Manag. 2017, 59, 567.
- [117] European Parliamentary Research Service report: Towards a circular economy – Waste management in the EU.
- [118] European Environment Agency, 2013.
- [119] WRAP report: Comparing the costs of alternative waste treatment options, 2017.
- [120] WRAP website, accessed October 2019.
- [121] PlasticsEurope report, 2016.
- [122] [Collection and Sorting of Household Rigid Plastic Packaging](#), 2012.
- [123] Zero Waste Scotland: A Business Case for Mattress Recycling in Scotland
- [124] WRAP report: Carpet and Mattress Recycling at HWRC Sites, 2015.
- [125] [RENUVA™ Mattress Recycling Program](#).
- [126] [BASF advances chemical polyurethane recycling](#).