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Closed Loop Recycling of Automotive Plastics - proposals for business sustainability

A Master's Thesis submitted for the degree of
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supervised by
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Affidavit

I, **DIPL.-ING.DR.MONT. RAMESH KUMAR SELVASANKAR**, hereby declare

1. that I am the sole author of the present Master's Thesis, "CLOSED LOOP RECYCLING OF AUTOMOTIVE PLASTICS - PROPOSALS FOR BUSINESS SUSTAINABILITY", 111 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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Abstract

Plastics have become one of the most important materials in the automotive sector due to their outstanding mechanical performances and high potential in weight reduction and thus enhancing the OEMs to reduce the carbon dioxide (CO_2) emissions of the vehicles. The European Union's regulations for limiting CO_2 emissions is one of the biggest challenges for the European automotive industry. On the other hand the European Commission's, End-of-life Vehicle (ELV) Directive requires higher recovery and recycling rates and reduce the amount of automotive shredder residue ending up as landfills. The increasing weight percentage of plastics in present new vehicles, will require high share of plastics recycling once they attain their end-of-life, to achieve the recycling targets. OEMs already started setting commitments to reduce waste and incorporate, for example up to 25% of recycled plastics materials in the new cars by 2025, which is a big challenge.

Polypropylene (PP), the largely used thermoplastics in the automotive has enormous potential as a new supply source for the automotive industry in attaining the regulatory requirements for end-of-life vehicles. But the current recycling process is very challenging in terms of costs, technology requirements and quality. The processing steps of automotive (AU) plastics recycling includes: dismantling, sorting & separating, shredding, up-scaling by compounding. The volume of polypropylene recovered from the ELVs are currently not high enough, which makes the recycled material cost unattractive for the customers.

This research focuses on analysing the automotive plastics closed loop recycling industry structure, the challenges and threats involved in the automotive plastics recycling process and finally to propose solutions to increase the plastics recycling volume, quality and their usage in the automotive sector, concentrating on the European market. The outcome of the study reveals that besides the ELV management, front loading of design for recycling during the plastics part development phase is crucial. This can avoid multi-material part design and hence ease the dismantling, sorting of materials from ELVs and additionally reduce the loss of plastic materials during ELV recycling process. The PP bumpers case study demonstrate that the standardisation of material specifications for automotive applications has great potential to increase the volume of quality feedstock for recycling.

Keywords Circular economy, plastics, automotive, closed-loop recycling, design for recycling

This thesis is dedicated to my son Valentin Sai.

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Nomenclature

ABS Acrylonitrile butadiene styrene

ASR Automobile Shredder Residue

AU Automotive

AV Autonomous Vehicle

CES Circular Economy Solution

CO_2 Carbon dioxide

EC European Commission

ELV End-of-life Vehicles

EPDM Ethylene Propylene-Diene Monomer

EPM Ethylene-Propylene Monomer

EU European Union

EuRIC European Recycling Industries' Confederation

EV Electric Vehicle

GHG Green house gases

HDPE High density polyethylene

HVAC heating, ventilation, and air conditioning

HWAS heat water air separator

LIDAR Light Imaging Detection and Radar

MPV Multi-purpose vehicle

NIR Near Infra Red

OEM Original Equipment Manufacturer

PA Polyamide

PC Polycarbonate

PCR Post-consumer Recyclates

PE Polyethylene

PET Poly-Ethylene Terephthalate

PIR Post-Industrial Recyclates

PMMA Poly methyl methacrylate

PP Polypropylene

PU Polyurethane

PVC Polyvinyl-chloride

REACH Registration, Evaluation, Authorisation and Restriction of Chemicals

RRR Reuse Recycling Recovery

SCOT Strength Challenges Opportunities Threats

SUV Sport Utility Vehicle

SWOT Strength Weakness Opportunities Threats

TPO Thermoplastic Olefin

WEEE Waste Electrical and Electronic Equipment

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"Your work is going to fill a large part of your life, and the only way to be truly satisfied is to do what you believe is great work. And the only way to do great work is to love what you do."

Steve Jobs

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Introduction

Plastics are ubiquitous in our daily lives, providing more functional and sustainable advantages. The usage of plastics is increasing drastically in different industry sectors, even though plastics are seen as the main culprit for the ocean and environmental pollution. Plastic waste has become one of the major economical issue, due to non-circular approach of plastic materials usage. As reported by McKinsey&Company [76], from the total plastic waste generated (260 million metric tons) in the year 2016 only 16% of the plastic waste was mechanically recycled, 25% was used in energy recovery, 40% of the waste ended up in landfills and 19% of the waste ended up in unmanaged dumps or leaks (see Figure 1.1). These leaks and the 4% of the waste material lost during the recycling process end up in the ocean or in landfills.

Several organizations, plastic material producers, Original equipment manufacturers (OEM)

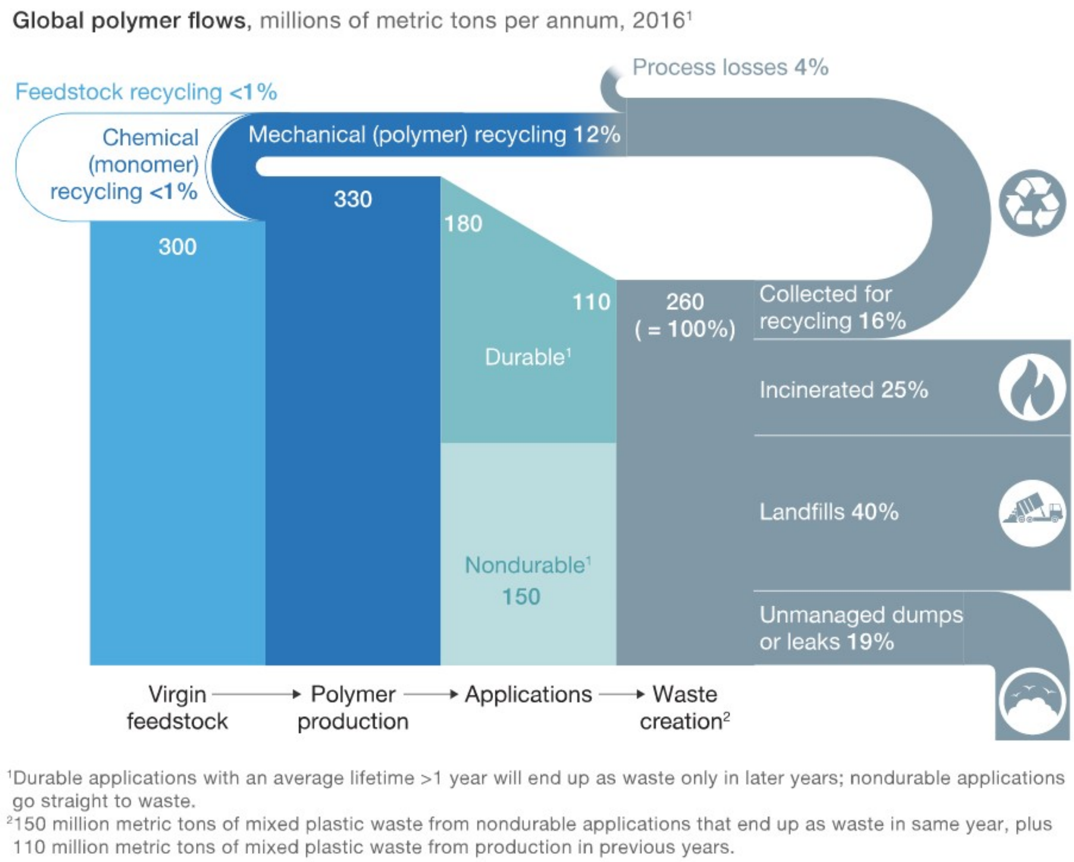

Figure 1.1: Global Polymer Flow [76]

have taken commitments and initiatives to reduce the plastic littering into the ocean or land filling by increasing the plastics reuse and plastic recycling (changing from Linear to Circular Economy). Increasing the recycling of post-consumer plastics could deliver significant environmental benefits. The current focus of most of the plastic circular economy projects are concerned to the packaging industry, which falls under the category of non-durable applications leading to high waste generation (Figure 1.1).

Automotive sector is the third largest industrial sector (after packaging and building & construction [62]), which uses high volume of plastic material. This quantity of automotive plastics are increasing, due to share of plastics in new cars are increasing and at the same time the number of cars manufactured globally is increasing too. The huge amount of plastic materials in the cars after the end of their life cycle (approximately after 10-11 years), will generate a huge volume of plastic waste. The need for using the automotive plastics in a sustainable and circular approach is already existing. End-of-life Vehicles (ELV) recycling plays a crucial role in maximising the recovery of high quality materials that can be recycled and reused in a closed-loop vehicle manufacturing system. But the challenges involved in recovering the plastic waste from the ELVs, recycling and reusing the materials in a closed-loop process are enormous. This thesis focuses on one of the main challenges "quantity" and propose solutions to tackle the insufficient quantity of good quality plastic recycled materials for the automotive applications and thus paving way for sustainable plastic usage in the automotive sector.

1.1 Background

Automotive industry is currently changing dramatically due to today's change in economies, which is highly triggered by new technologies, sustainability policies, new emerging markets, digitalization, automation, change in customer preferences around ownership and new business models. These economic influences are forcing the automotive industry towards four disruptive technologies: diverse mobility, autonomous driving, electrification and connectivity [56]. Additional to the economical threats, the car manufactures are facing more legislative pressures to reduce the emission levels and reduce the waste generated by ELV. The European Union (EU) is focused more on the environmental sustainable waste management and has introduced a road-map to a resource efficient Europe and circular economy package to make EU's economy sustainable by 2050. The directive on end-of-life vehicles, one of the four EU directives, incorporates mandatory extended producer responsibilities to introduce more greener products into the market and support recovery and recycling schemes for ELVs [32].

Plastics are the second highly used material in the automotive sector, after metals. A modern automobile's volume has up about 50% parts made out of plastics, but only 10% of it's total weight and this value range up to 15% [60, 62, 74] in an average. Due to it's light weight, plastics usage is becoming more in the new vehicles, replacing metals and thus reduces the vehicle weight, fuel or energy consumption and CO_2 emission. In the development of new electric vehicles, plastics and their composites play a vital role in reducing the car mass to enhance longer distance coverage with battery.

The concerns over the environmental pollution and global climatic changes are impulsing the manufacturers and consumers to utilize the circular approach of using materials or products, such as product recovery, waste management, reusing products before disposal or usage of recycled materials. Moreover recycling of plastics from ELVs and reusing them in the new vehicles will enhance the OEMs meet the requirements of European Directive and also lower the CO_2 footprint of their products.

Most of the leading OEMs in Europe have set targets to launch new vehicles containing high percentage (up to 25%) of recycled plastics. For example Volvo Cars, recently published their aim of using 25% recycled plastics in cars from 2025 and also demonstrated their a demo version of the XC60 T8 plug-in hybrid car, which has over 60kg of its plastic parts replaced with part made out of recycled materials [81]. Tostar from Volvo Cars, in the International PIAE Congress Germany in 2019 [77], mentioned that the content of the recycled-plastics is calculated on the basis of the actual weight of recycled plastic in a component and not by the weight of the entire component that contains a portion of recycled plastic . To realize this vision, Volvo has specified for every new car a recycled plastics target in kilos/vehicle, which is spread over the various design engineering departments.[77].

Groupe Renault has taken initiative to increase the overall use of recycled plastics by 50% from 2013, in order to support the French government's Circular Economy Roadmap, which is focusing towards 100% plastic recycling rate in France by 2025 [38]. Jean-Denis Curt, Head of the circular Economy Division at Groupe Renault stated

"*As a carmaker, we must limit the environmental footprint of our products and activities as much as possible in order to address the issues of global warming, air quality and the increasing scarcity of natural resources. It is with this in mind that via our automobile business, we have just given the French government reaffirmation of our goal to increase our overall use of recycled plastics by 50% from 2013, or 64,000 tons for all of Groupe Renault.*"[38].

Jaguar Land Rover (JLR) is trialling an innovative recycling process (chemical recycling process) that converts plastic waste into a new premium grade material which could feature on future vehicles, together with chemical company BASF. Also at JLR, the usage of recycled material content in their new products is proactively increasing. Chris Brown, the senior sustainability manager at JLR mentioned

"*Plastics are vital to car manufacturing and have proven benefits during their use phase, however, plastic waste remains a major global challenge. Solving this issue requires innovation and joined-up thinking between regulators, manufacturers and suppliers.*"[44].

These initiatives from the OEMs show a growing demand for recycled plastics in the car industry.

1.2 Problem Description

The demand for recycled plastics in automotive industry is getting more attention due to several factors, as mentioned already in section 1.1. There are two sources of feedstocks (plastic waste), which can be recycled, upgraded and used for new part manufacturing. They are:

- Post industrial plastic waste
- Post consumer ELV plastic waste

More than 80 % of the feedstocks are currently derived from manufacturing scraps [36]. Even though the recycling of post consumer plastic domestic waste is growing, the usage of domestic plastic waste recyclates in the automotive applications is not possible without upgrading, due to quality and performance issues. In order to fulfill the OEM's high quality requirements both for virgin and recycled polymers, alternative feedstocks with much better quality and purity is required for automotive applications. Apart from the post industrial plastic waste, the best suitable source of feedstock is the end-of-life vehicles. This process of recycling the used plastic parts from ELVs and producing new parts for new cars is called the closed loop recycling. According to the Eurostat statistics, in an average 6.6 million cars are reported as end-of-life vehicle between years (2008 - 2016) in EU-28 [33]. World wide 27 million vehicles reach their end-of-life after an approximate 11 years of service life [74]. According to the EU Commission [29], every year between 7 million to 8 million tonnes of waste is generated by ELVs in the European Union. The ELV generated in year 2015 consisted around 12% of plastics and process polymer waste and the Polypropylene (PP) contribution was around 40% [40]. Due to the high diversity in ELVs collection system and the high variations in the quality level of the dismantling system available, the collection of the value materials embedded in the ELVs become very challenging [79]. Additionally the product design and different material combinations increase the complexity of the dismantling, sorting and hence the recycling process. Through these technical complexities of the recycling process, the price of recycled plastics materials are not attractive for the OEMs or the Tiers.

According to Volvo [81] and Renault [79] there are several challenges involved in using recycled plastics in the new vehicles, which are:

- quantity of feedstock for recycling
- recycled plastics available in the market
- quality of the feedstock and the recycled plastics
- price of recycled plastics not cheaper than virgin materials
- chemical substance regulations

Some feasible solutions are required to increase the volume of feedstocks for the closed loop plastics recycling and thus increase the market availability of good quality recycled plastics for automobile applications, which is economical too.

1.3 Research Objectives and Questions

Considering the recycled PP material availability in the market, one of the biggest challenges currently faced by the automotive industry in introducing sustainable recycled plastics in new cars, the problem definition is paraphrased into following main question: *"What could be the potential solutions to increase the volume of closed loop recycled Polypropylene for the automotive applications?"*

Following sub questions are formulated to concretize the above mentioned main research question.

- Does closed loop recycling of AU plastics has economical, ecological and technical advantages for the whole AU supply chain?
- What are the challenges in the AU plastics closed loop recycling models?
- How can the plastic sorting from ELVs made simpler and efficient?
- How can OEMs plastic material specification standardization and front loading of design for recycling rules improve the plastics circular economy?

In order to answer the above mentioned research questions, the objectives of this thesis are formulated as:

- Understanding the bottlenecks of closed loop recycling of Automotive plastics, focusing on polypropylene, through qualitative data research (interviews with plastic recyclers and plastic compounders, ELV recyclers - focus the European Market).
- SWOT analysis of closed loop plastic recycling in the automotive industry through experts brain storming.
- Definition of several design for recycling rules in the OEM plastics part as well as material specifications (front loading).
- Theoretical study on the advantages of standardising the PP material specification from recycling point of view using PP Bumpers case study. The hypothesis is, if the PP bumper material specification is standardised, then the material losses during the recycling process can be reduced.
- Researching market demand for the recycled plastics in automotive and state of the art concerning automotive plastic trends and closed loop recycling models in automotive industry.

1.4 Thesis Structure

This introduction section (chapter 1) gives an overview about the background and the main objectives covered in this research. The research methodologies used for answering the research questions are summarized briefly. Chapter 2 provides the market review (secondary data) over the virgin plastic material usage trends in the automotive sector and application trends of recycled plastics in new cars. Also in this chapter the market review of ELVs, EU commission's ELV directives and their future strategies for the plastic circular economy are briefly mentioned. Details on the state of the art closed loop recycling of plastics, their advantages, the bottlenecks involved are highlighted.

In chapter 3 the scientific approaches used in this research for gathering the primary data, through structured interviews with experts from the plastic recycling and ELV plastics recycling industry sectors, is detailed. The theoretical comparison of the different PP grades available in the European market for the bumper application (case study) is be elaborated. With these data, the effectiveness of standardizing the OEM material specification are theoretically examined. The workshops conducted with group of experts from the Automotive and Circular Economy Solution department for analysing the SWOT of the closed loop recycling of automotive PP and also outline some suggestions for the design for recycling rule, both on material and plastic parts, is briefed. All the outcome of the interviews, workshops and the theoretical analysis performed under chapter 3 are presented with elaborate discussions in chapter 4.

Chapter 5 draws conclusions from the analysis made on the close-loop recycling of PP with some proposals to the EU commission and the OEMs for improving the sustainable usage of plastics in the automotive industry.

1.5 Research Methodologies

This scientific research work is done combining both theoretical and empirical research methodology. For the collection of primary data a mixed approach of both qualitative and quantitative tools are used. The secondary data are gathered through literature research, online research and through case study research. Interview technique is the tool used for qualitative research. Semi-structured interview method with a fixed set questions in a standardized manner is utilized in this research. This interview method combined predefined questions like in a structured interview with the open-ended exploration of an unstructured interview [82]. The main intention of using this method is to gather systematic information about closed-loop plastic recycling, while also allowing some exploration when new topics emerge during the interview. Moreover in the semi-structured interview methodology both open-ended and closed-ended questions can be used and this lead to retrieval of both quantitative and qualitative data [82]. Group discussions and brain storming methodologies are used for the SWOT analysis and PESTLE & Porter's Five Forces analysis respectively.

"Marketing is not the art of finding clever ways to dispose of what you make. Marketing is the art of creating genuine customer value. It is the art of helping your customer become better off. The marketer's watchwords are quality, service, and value."

Philip Kotler

2

Literature and Market Research

Marketing is a management philosophy, according to different marketing experts. The marketing has generalised five step process (see Figure 2.1) [51]. As shown in figure 2.1 the first and the foremost step of the marketing process is to analyze the market. This market analysis include the thorough understanding of the firms own capabilities, customer requirements, future trends, future market scenarios and what the competitors are doing.

This basic market study will reveal the gaps between what customers want and what currently offered to them, then there may be opportunities to develop and introduce new products, which better satisfy the customer requirements. Market research will provide specific market information, which permits the firm to define the target market segment. Considering the results and identified opportunity a strategic plan for pursuing the new opportunity

Figure 2.1: Marketing steps [51], modified by the author

can be developed. This chapter summarizes the market findings on the usage of plastic materials in the automotive industries, their future trends, circular economy models of plastic life-cycle, European strategy for plastics and an overview on European Commission (EC) ELV directives.

2.1 Automotive Trends

According to the pwc report, the car of the future is electrified, autonomous, shared, connected and yearly updated - in a short form "eascy" [35]. The global automotive customer study made by Deloitte 2019, where more than 25000 customers in 20 countries across the globe were surveyed, explores the latest data and insights around automotive consumer trends in 2019. The report highlights the four major trends (Figure 2.2) namely: Autonomous vehicle (AV), Electric vehicle (EV), Connectivity and Shared mobility. The key insights of the survey are [18]:

- AVs are considered as unsafe by most of the customers and they doubt if this technology is applicable for the real world.
- Due to supportive environmental policies and shifting consumer attitudes the demand for the EVs is going in EU and also in Asia Pacific but in North America the demand is less due to low fuel prices.
- Concerning connectivity, consumers opinions are mixed while some interest is there in the time-saving features but most consumers are concerned about the privacy and data security.

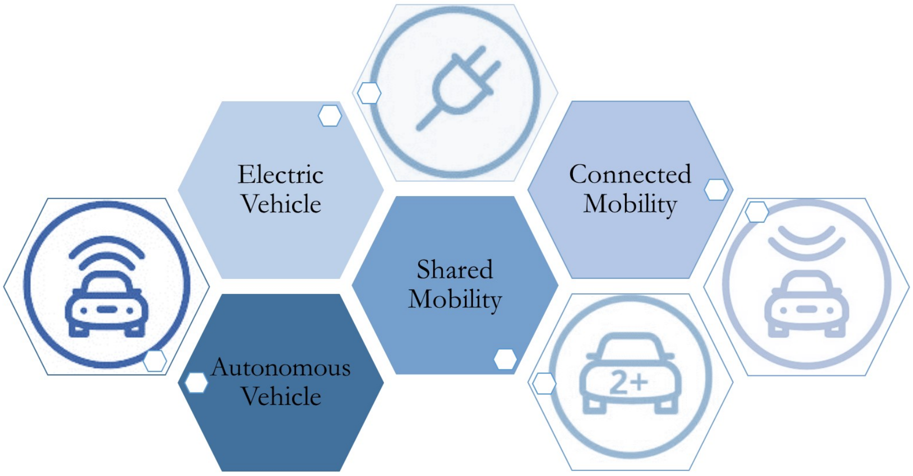

Figure 2.2: Global automotive trends - 2019,

- Shared mobility future could be a hinge on younger generation, who have fully embraced the precepts of a digitally enhanced existence.

The Mckinsey&Company report over the automotive revolution towards 2030 confirms that the digitalization and new business models are giving rise to the above mentioned four disruptive technology trends [56]. The above mentioned automotive trends are triggering the development of new technologies and materials. When considering the materials side, polymers and their composites are gaining more importance due to their light weight, good mechanical performance, price and easy processability. The inclusion of glass or carbon fibers to plastics especially is more focus, to replace metal parts in the vehicles. The reduction of car weight by 1 kg will lead to 20 kg less CO_2 emission over the car's operation life time [61].

2.2 Plastics Market in Automotive - Current and Future Trends

2.2.1 Plastics - European Market Data

The plastics family, which is composed of variety of materials design to meet the different requirements of several thousands of end applications, are categorized into two main groups.

- Thermoplastics - the plastics family which can be easily recycled. The materials melt on heating and hardens on cooling. Some examples: Polyethylene (PE), Polypropylene (PP), Polyvinyl-chloride (PVC), Polyamide (PA), Polycarbonate (PC), Poly methyl methacrylate (PMMA) etc.

- Thermosets - the plastics family which cannot be recycled. The material undergoes chemical changes and hardens on heating. Some examples: Polyurethane (PU), Epoxy resins, Silicone, Melamine resins etc.

According to the PlasticsEurope the global plastics production was 359 million tonnes in the year 2018, which is 3% more than the previous year [64]. In Europe (EU28+NO/CH), the plastics production volume was 61.8 million tonnes [64]. Considering the global plastics production distribution in the year 2018, Europe (17%) is the third largest producers of plastics after China (30%) and NAFTA (18%) [64]. The European (EU28 Member States) plastics industry, which includes plastics raw materials producers, plastic converters, plastic recyclers and plastics machinery manufactures, employs more than 1.6 million people in Europe and had a turnover of 360 billion euros in the year 2018 [64]. The plastics raw material producers and plastics converters in the European plastics industry had a trade balance of more the 15 billion euros in 2018 [64].

The main market sectors for the plastics materials are: packaging, building & construction, automotive, electrical & electronic, household/leisure &sport, agriculture and others (like medical, furniture, technical parts for machine building, etc.). As shown in Figure 2.3 the packaging industries in Europe have the highest demand (around 40%) of plastics, followed by building & construction (around 20%). Automotive sector is the third largest consumer of the plastics globally and in Europe with a converter demand of 10.1%. The usage of plastics in the automotive applications is increasing rapidly. In 1950s the amount of plastics that could be found in an vehicle was 0. But in the modern average cars around 2000 parts are made out of plastics and around 225 kg of plastics can be found on board of a modern mid-range car [61].

Figure 2.3: Plastics demand by segments and polymer types in 2018 data for EU28+NO/CH (51.2Mt) [64]

2.2.2 Plastic Demand - Automotive Applications

On an average, a vehicle (weighing around 1,100 kg) consists of 16% of plastics (approximately 176 kg of its total weight). This equates to over 2000 different plastic parts of varying shapes and sizes; from bumper and lights, to engine components, dashboards, headrest, switches, clips, seats, airbags and seat-belts [60]. In 2018 the demand of plastics for automotive segment in Europe was around 10% (Figure 2.3).

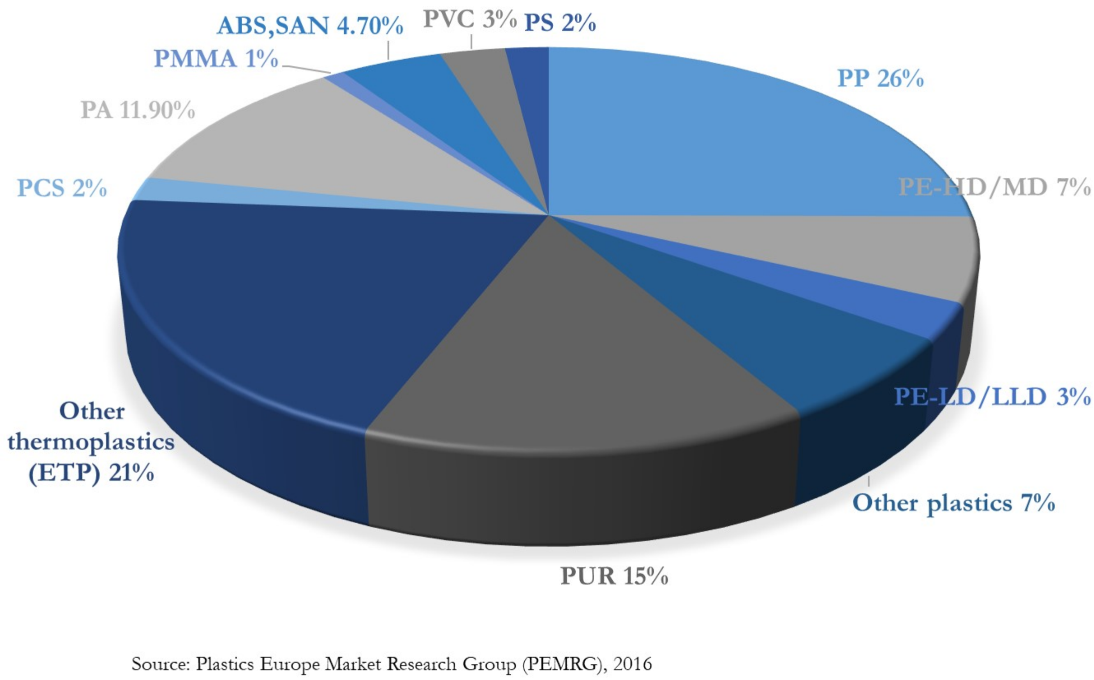

Figure 2.4: Plastics use in the automotive segment, Europe,2016 [61], modified by the author

Focusing on the different resins European demand in 2017 and 2018, PP material dominates with around 19.3% for varying applications like food packaging, sweets and snack wrappers, caps, pipes, automotive parts, etc. [62, 64]. In 2016, around 5 million tonnes of plastics was used in the European automotive industry. The contribution of different plastic materials used in the automotive industry is shown in Figure 2.4 for the year 2016. Also in the automotive applications, among the different plastic resins used, PP dominates with 26%. The demand of different plastics in the automotive applications varies considerably, due to the performance and the properties of the resins. For example the Tier suppliers, manufacturing bumpers need high volume of PP where as seat manufacturers typically buy high volume of PU. Depending on the parts application and function, the product composition varies accordingly [16]. Based on the application and plastic part performance requirements, the plastics are used in different variants: unfilled, mineral filled, glass fiber (GF)/ carbon fiber (CF) filled, natural or colored, etc.. The application areas of plastics in the automotive sector can be grouped as interior, exterior, under the hood and electric/light. In 2016, more than half of 5 million tonnes plastics (53%) was consumed for car interior applications, 20% was used for the exterior, for the parts under the hood 14.5% and for lighting and electric applications 13% of plastic materials were consumed in Europe (Figure 2.5) [61].

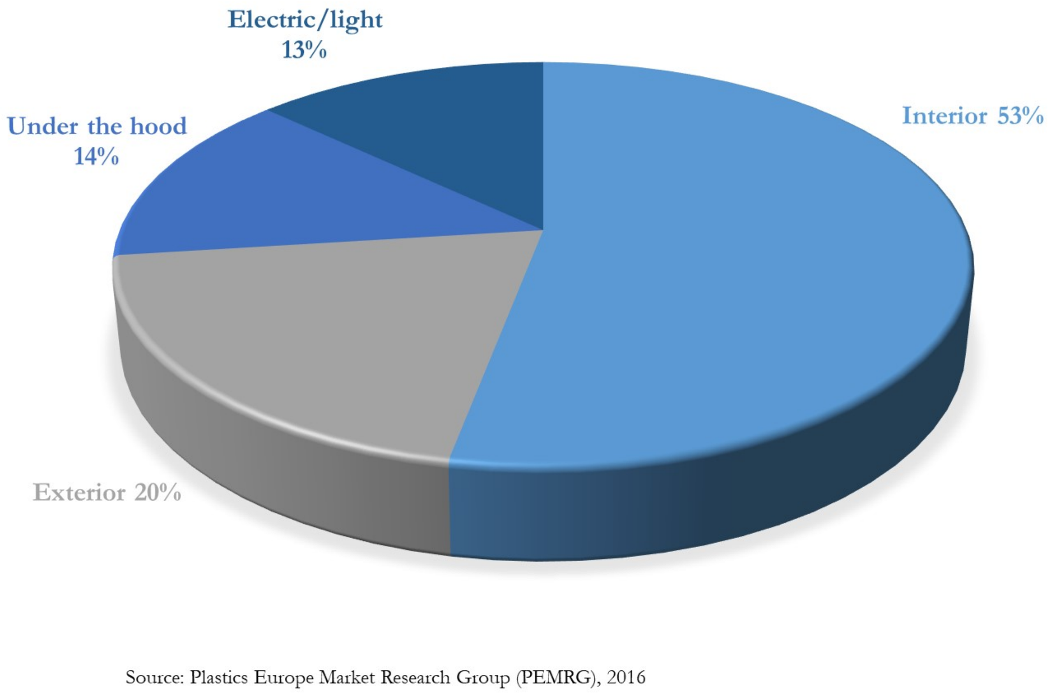

Figure 2.5: Plastics parts use in the automotive segment in Europe,2016 [61], modified by the author

The property requirements of the plastics vary according to the application area. For example plastics used in the interior requires good aesthetics, haptics, high purity, neutral odour, light weight, good stiffness and impact properties etc. [10], whereas for the exterior applications the requirements concentrate on the paintability, toughness properties, weather resistance, stability etc.[9]. Under the hood materials mainly require high temperature stability, resistance to corrosive fluids, extreme durability maintaining the surface properties [14]. The automotive parts with high consumption of plastics, as mentioned by CBI

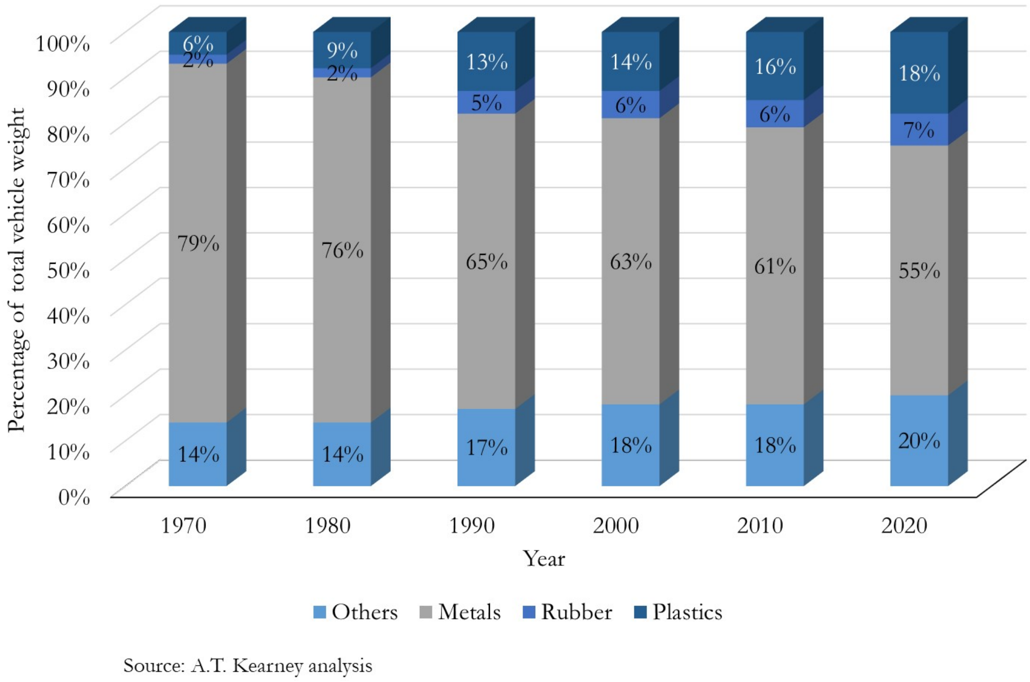

Figure 2.6: Material composition in automotive - Trend [37]

[16] include the interior trim (approximately 21 kg), seating (approximately 14 kg), bumpers (approximately 9 kg), upholstery, electrical components and dashboards (all together about 8 kg).

2.2.3 Automotive Plastics - Future Trends

The usage of plastics in the automotive vehicles has almost tripled in the past 50 year. Figure 2.6 shows the composition of materials used in the vehicles and their changes from 1970 to 2020. In 1970 and 1980 the usage of plastics in cars was less than 10%. The plastics materials contribution was 16% in a vehicle, leading to a weight of 224 kg of plastics considering an average vehicle weight of 1400 kg in the year 2010 [37]. This situation according to the report of ATKearney [37] will change, where the cars of 2020 will have 18% share of plastics, around 198 kg of plastics, whereas the average weight of the cars will reduce to 1100 kg due to increased share of plastics replacing the high density metal parts. The four future trends in the automotive industry (see 2.1), requires not only advanced technologies but also advanced material solutions.

AUTONOMOUS DRIVING: Self-driving cars technology is developing too fast and soon such vehicles will be seen on the roads. Detection systems for autonomous vehicles use "radio-frequency-transparent" plastic front-ends, reading the road ahead. The light weight of the plastics can be advantageous in reducing the total weight of the autonomous car weight and thus can preserve the battery ranges [4]. The usage of different sensors, navigation systems, infotainment, interactive display interior equipment, durable and hygienic interior material can be easily shaped by using polymer materials [4]. Safety is a fundamental priority when it comes to fully autonomous vehicles, which can drastically reduce crashes. Plastic materials play a vital role in enhancing the safety of the autonomous driving vehicles by enabling seat belts, airbags, side-curtain bags, windshield inner-layers, pedestrian collision protection safety features and padded dashes [4].

The usage of varying type of sensors in the autonomous vehicles, like Light Imaging Detection and Radar (LIDAR) sensors can be invisibly integrated into thermoplastics design of a vehicle's parts [4]. The use of high number of sensors in an vehicle cannot avoid the usage of plastics wiring, harnesses and connector, which are crucial for the autonomous vehicle deployment and life saving safety features.

CONNECTED VEHICLES: For a good vehicle-to-vehicle communication, signal transparency or permeability of material is a pre-requisite and this can be achieved by using plastics. The plastics materials can be tailor made to allow certain radio frequency signal wavelengths to pass through them, undisturbed [4].

RIDE SHARING: Plastic materials due to their easy moldability, low density can enhance weight efficiencies of ride-sharing vehicles [4]. Autonomous vehicle ride sharing will equip more computational, data transfer and digital display equipment on board to navigate the vehicle. Plastics can conserve weight, consolidate parts and make space for the required electronics and electrics. Carbon fiber composites will enhance vehicle safety and provide more security in autonomous ride sharing, at the same time reduce vehicle weight by replacing many metal parts [4].

EV TECHNOLOGY: When it comes to fully electric vehicle drive technology, the weight of the car is one crucial parameter to be consider for increasing the mileage of the battery. This can be achieved through usage of more lightweight plastics and compact space-saving structures made out of plastics and their composites. The plastics in both EVs and hybrid vehicles will protect the electrical and electronic parts from corrosion or moisture and due to the sound deadening properties, also helps to reduce noise [4].

INFOTAINMENT: With the concepts of self-driving vehicles, the interior design concepts are changing enormously for example to bring the living room effects. Different automotive interior suppliers together with OEMs are developing concepts for the interior design of the future self-driving cars with more comfort for both drivers and passengers. Light weighing, high gloss plastic display technologies on the outside surface of the cars, and in-vehicle displays, even transparent displays made out of plastics, have evolved to incorporate emerging technologies allowing popular apps and those of tomorrow [4]. High scratch-resistant plastic materials for the display screens can be very helpful to prevent vandalism in shared vehicles [4].

SUSTAINABILITY: Automotive industry is moving towards sustainability in their products by introducing more sustainable materials like recycled materials and natural materials in the automotive parts, for two main reasons:

- to achieve their own sustainability goals and target
- to achieve the targets set by the EU circular economy plastic strategy (refer section 2.3)

The usage of sustainable and recycled materials can reduce the carbon foot print of the cars. Usage of bio-polymer and composites using natural fibers in cars are getting more attention. For example incorporation of recycled PP material have a positive impact on environmental footprint, with a 30% less CO_2 emission than virgin PP material [13].

2.3 EU Commission- Plastic Strategy

Considering the alarming problem of million tonnes of plastic waste ending up in the ocean and affecting the ecological system, the European Commission took initiative to tackle this environmental issue by introducing in the year 2015 the CIRCULAR ECONOMY action plan: CLOSING THE LOOP [26]. Within this action plan, EU identified plastics as key priority and committed itself in preparing new strategy for the whole plastic value chain and plastic life cycle. According to European Commission COM(2017)479 "*The plastics industry is very important to the European economy, and increasing its sustainability can bring new opportunities for innovation, competitiveness and job creation, in line with the objectives pursued by the renewed EU Industrial Policy Strategy.*"[27].

The main cause for this plastic littering problem is that, plastics are currently produced, used and discarded, failing to utilize the economic and environmental benefits by using the plastics in more "circular" approach. In the European strategy for plastics COM(2018)28, it is stated that "*The EU is best placed to lead the transition to the plastics of the future. This strategy lays the foundations to a new plastics economy, where the design and production of plastics and plastic products fully respect reuse, repair and recycling needs and more sustainable materials are developed and promoted. This will deliver greater added value and prosperity in Europe and boost innovation. It will curb plastic pollution and its adverse impact on our lives and the environment. By pursuing these aims, the strategy will also help achieve the priority set by this Commission for an Energy Union with a modern, low-carbon, resource and energy-efficient economy and will make a tangible contribution to reaching the 2030 Sustainable Development Goals and the Paris Agreement.*" [28].

The focus of EU commissions' plastic strategy is also to recognize the challenges involved the in ,low reuse and recycling rates of plastic waste, the greenhouse gas emissions associated with plastics production and incineration, and the presence of plastic waste in oceans [28]. The EU circular economy strategy focuses its action plans on the EU level and these commitments are only achievable through combined efforts of different private sectors, non-profit organizations, national and regional authorities, cities and citizens. The intention of the EU is to develop the circular economy globally [26]. The new plastic economy according to Ellen MacArthur Foundation [20], shown in Figure 2.7, aligns with the principles of circular economy (Figure 2.8), an industrial system which is restorative and regenerative by design. The ambition of this new plastic economy is to deliver better system-wide economic and environmental outcomes by creating an effective after-use plastic economy, by reducing the leakage of plastics into the nature and by adopting renewable sources of feedstocks instead of fossil feedstocks for plastics production [20].

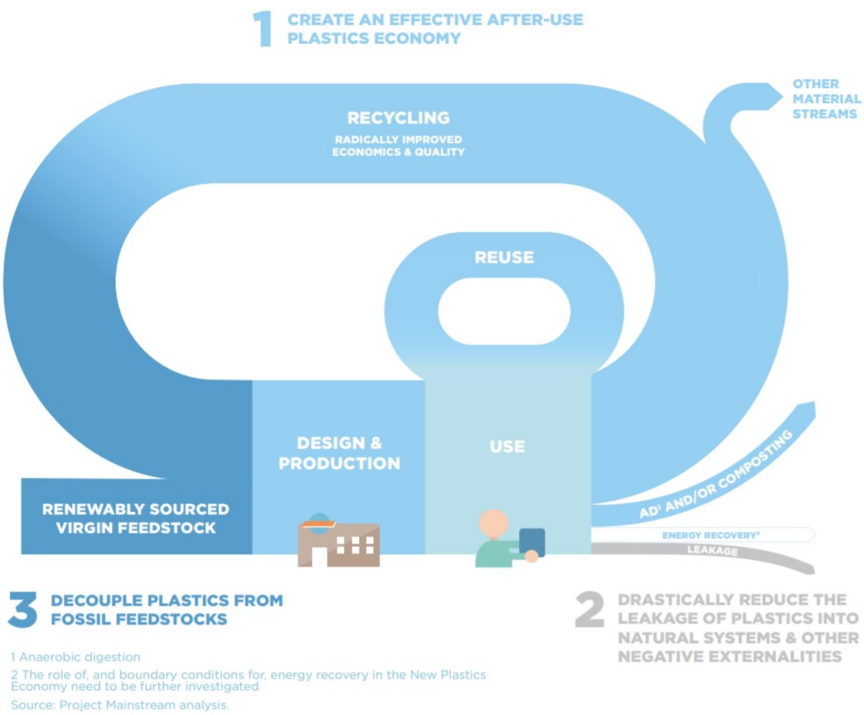

Figure 2.7: New plastics economy - based on circular economy [20]

What is circular economy? According to Ellen MacArthur Foundation "*The circular economy refers to an industrial economy that is restorative by intention; aims to rely on renewable energy; minimises, tracks, and eliminates the use of toxic chemicals; and eradicates waste through careful design.*"[19]. The circular economy model replaces the concept of the end-of-life with restoration concept, avoid the use of toxic or fossil substances, focuses on reuse of products and aims at the elimination of waste through superior design of materials, products, systems, and business models [19]. This circular economy model consist of following simple principles [19]:

1. Waste does not exists - products are designed and optimised for easing disassembly and reusing or recycling.
2. Difference between consumable and durable components
   - Consumable in circular economy are made of biological ingredients
   - Durables are made of technical nutrients likes metals or plastics, which are designed from the beginning for reuse.

3. The required energy for fueling this cycle should be renewable by nature.

The above mentioned principles drive following four sources of value creation, to increase material productivity [19]:

- Power of the inner circle - minimising comparative material usage
- Power of circling longer - maximising the number of consecutive cycles (reuse, remanufacturing or recycling)
- Power of cascaded use - diversifying reuse across the value chain
- Power of pure circles - uncontaminated material streams increase collection and redistribution efficiency while maintaining quality

Some of the key points of the Europe's new plastics circular economy are listed as follows [28]:

- Smart, innovative and sustainable plastics industry, where the product design and parts production fully respects the needs of reuse, repair and recycling enhancing to reduce the EU's greenhouse gas emissions and their dependence on fossil fuels.
- Plastic materials and their products are designed for great durability, reuse and high-quality recycling.
- More than half of the plastics waste generated in Europe is recycled, by 2030.
- Reach very high levels of separate collection systems for plastics waste.
- Increase the volume of sorting and recycling capacity by fourfold from 2015 to 2030.
- Far more integration of the plastic value chain, from the chemical industry to plastics recyclers.
- Successfully establish the market for recycled and innovative plastics, with clear growth perspectives as more products incorporate some recycled content.

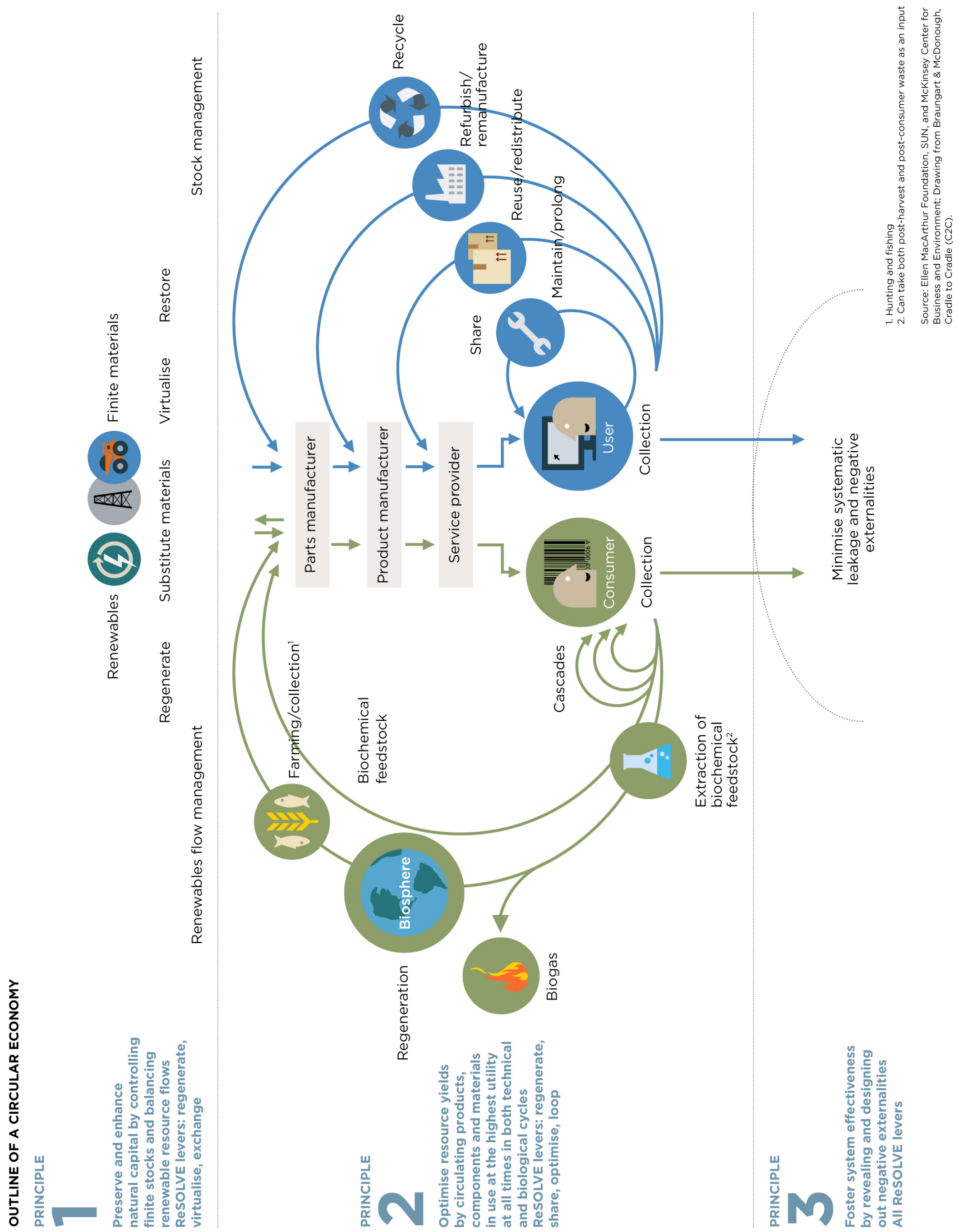

Figure 2.8: Circular economy model [22]

- The demand for the recycled plastics grow fourfold in Europe, creating a stable revenue flow for the recycling industry.
- High plastic recycling volumes helps to reduce the dependence of Europe on the important fossil fuels and at the same time reduce the CO_2 emissions, in line with the commitments taken under the Paris Agreement.
- Development and usage of innovative materials and alternative feedstocks for the production of plastics, which are more sustainable.
- Europe to be leader in sorting and recycling equipment and technologies.
- The European citizens, government and industries support usage of more sustainable and safer consumption and production patterns for plastics.
- Decrease the leakage of plastics into the environment drastically, especially microplastics entering the ocean.
- The EU as a leader in engaging the countries and industries to prevent plastics waste flow into ocean.

Taking a deep dive into the effects circular economy of business model on costs and emission reduction (Figure 2.9), show that the circular economy, capable of reusing and recycling a greater share of materials, would prevent economic loss for different industrial sectors and this can be beneficial to both the producer and the user. The circular economy solutions can be highly cost-effective compared to cutting green house gas (GHG) emissions through emerging technologies that are still expensive [23]. Concentrating on the recycling of plastics, reusing of plastics, usage of lighweight materials in the cars (Figure 2.9 have high benefits on the CO_2 emissions reduction.

According to the PlasticsEurope (2019b) report, 29.1 million tonnes of plastic post-consumer waste was collected in the year 2018, which is 19% more than in 2006 (24.5 million tonnes)[64]. In Europe the recycling of post consumer waste has doubled in the past 12 years (see Figure

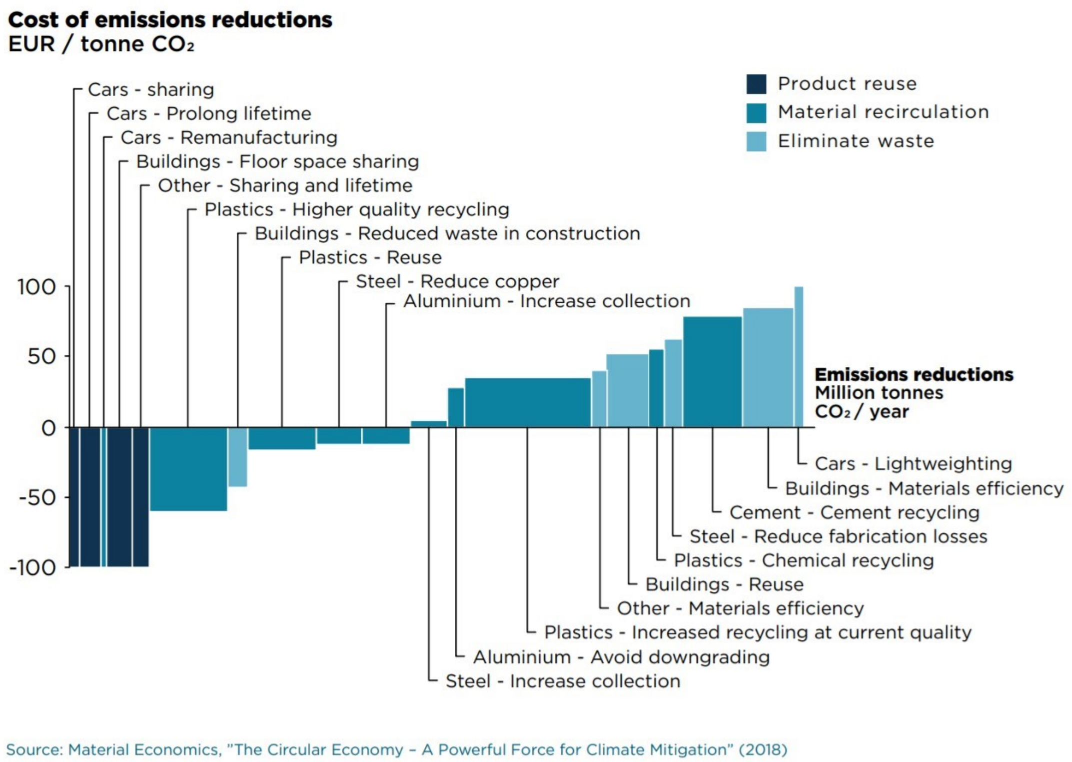

Figure 2.9: Circular economy - emission reductions [23]

2.10). Currently only 32% of the collected plastics are recycled in Europe, where as 43% of the waste is used for energy recovering around 25% waste still goes in to landfills.

Despite the reduction of landfill volume of plastic waste by -44% from 2006 to 2018, still 7.2 million tonnes of plastic waste end-up in land filling, causing environmental pollution. The percentage of waste used for energy recovery has increase by +77%. The export of plastics waste outside Europe has decreased by -38% from 2006-2018 [64]. These numbers show that, there is still a huge potential for increasing the recycling volume and reducing the waste going into the energy recovery or ending up in landfill. The new plastics circular economy strategy action plans initiated by the European Commission, will lead to zero % landfill and increase the reuse, recovery and recycling numbers gradually before 2030.

The European Commission presented an action plan on the circular economy in December 2015, and additionally four legislative proposals amending the following legal acts: (a) Waste Framework Directive; (b) Landfill Directive; (c) Packaging and Packaging Waste Directive; and (d) Directives on end-of-life vehicles, on batteries and accumulators and waste batteries and accumulators, and on waste electrical and electronic equipment (WEEE) [32].

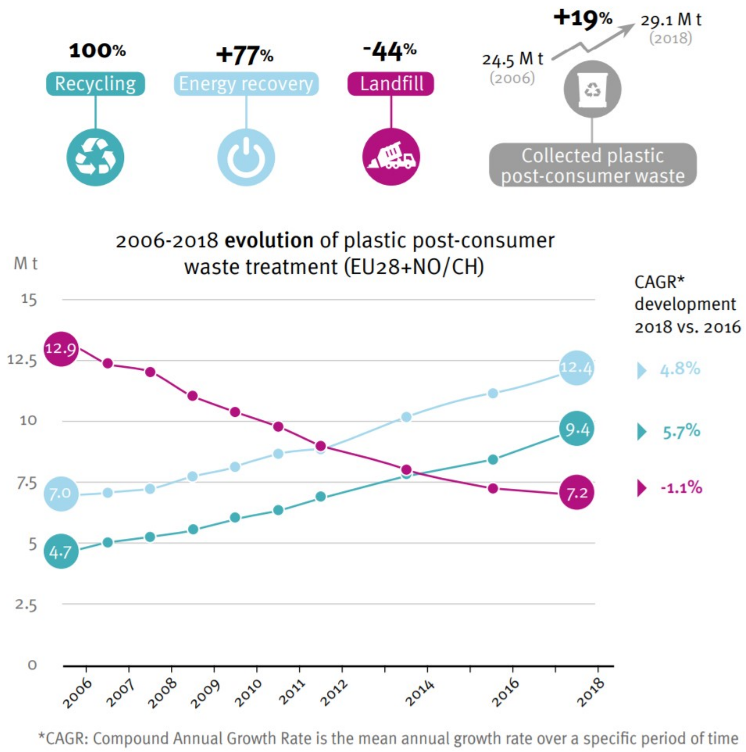

Figure 2.10: Post consumer plastic waste treatment in EU28+NO/CH [64]

2.4 EU Commission - ELV Directives

In Europe every year end-of-life vehicles generates 8 to 9 million tonnes of waste, which must be managed properly to reduce the waste ending up in landfills. In order to manage the ELVs, the European Parliament released the Directive 2000/53/EC on the End of life Vehicles in 2000. The main objective of the directive is to minimize the environmental impact of the ELVs, setting some preventive actions like designing new vehicles taking into account dismantling, reuse and recycling and to drive the circular economy in the Automotive sector. The fundamental principle of the directive is that "*waste should be reused and recovered, and the preference be given to reuse and recycling.*" [25].

According to Directive 2000/53/EC the targets until 2006 was -"*the no later than 1 January 2006, for all end-of life vehicles, the reuse and recovery shall be increased to a minimum of 85% by an average weight per vehicle and year. Within the same time limit the reuse and recycling shall be increased to a minimum of 80% by an average weight per vehicle and year;*"[25] and target until 2015 was : "*no later than 1 January 2015, for all end-of life vehi-*

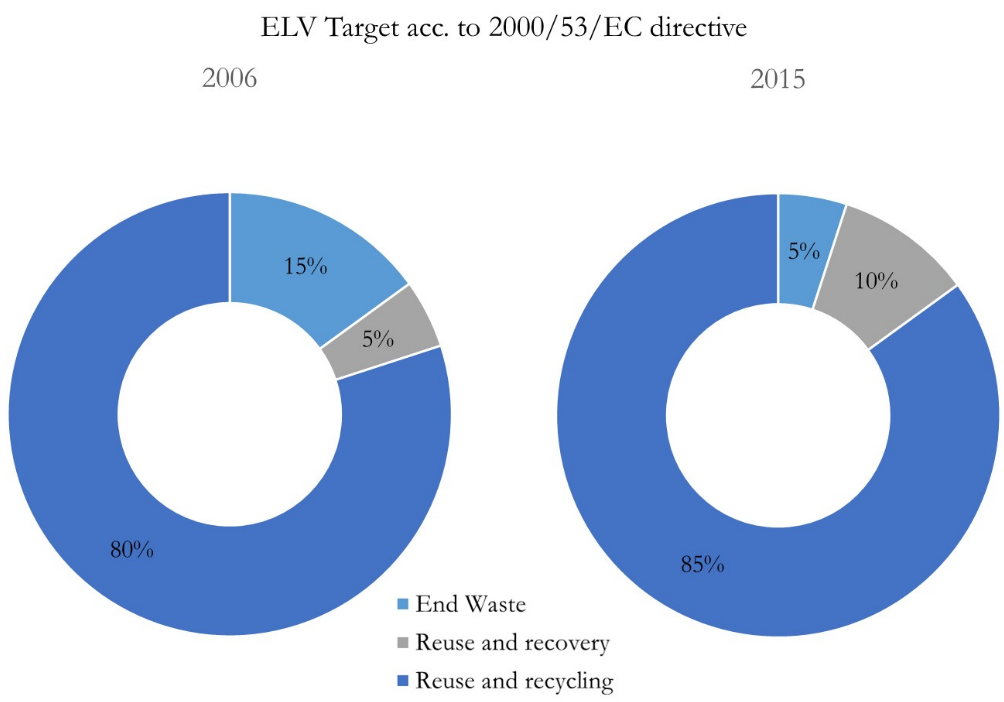

Figure 2.11: Targets of the ELV Directive 2000/53/EC for 2006 and 2015

cles, the reuse and recovery shall be increased to a minimum of 95% by an average weight per vehicle and year. Within the same time limit, the re-use and recycling shall be increased to a minimum of 85% by an average weight per vehicle and year." [25] (see Figure 2.11).

In order to meet the targets of the ELV Directive, the usage of recycled materials in car parts or components manufacturing in Europe is increasing. The technical focus is on post-consumer and post-industrial waste sources, which are of high quality standards. The proposed EU strategy for plastics may require the use of a further 10 million tons of recycled plastics, from across all industries, by 2025. According to the theoretical estimation made by Deloitte, 30% of the plastics waste in the ELV to be recycled for reaching the over all target of the ELV Directive by 2020 and for 2025 the plastic recycling share is predicted to be 35% [55].

The Eurostat data (see Figure 2.12), shows that between years 2008 and 2016, around 6-7 millions cars were registered as ELVs and treated compliant with ELV Directive in Europe. Comparing the car production history and the ELVs registered in Europe, it is very clear that around 4 million vehicles of unknown whereabout per year exist in Europe [24]. To eradicate the issue with large number of vehicles of unknown whereabouts in Europe and to make dismantling and recycling of ELV easier, the European Recycling Industries' Confederation (EuRIC) published the Roadmap to review and evaluate the Directive 2000/53/EC on end-of-life vehicles (ELV Directive) by the European Commission. As mentioned in the EuRIC Roadmap [24], the reasons for missing vehicles might be illegal exports, statistical errors, misuse of the temporary deregistration of vehicles etc. The ELV Directives are taking steps to improve the ELV management and reduce this gap between the new registration and the ELV registration per year. Moreover ELV Directives is also focusing to achieve new technologies for the ELV treatment, advanced software tools like information for dismantling and parts (IDIS) for proper dismantling of parts from the ELVs and proper treatment of recovery/recycling of all valuable materials [41].

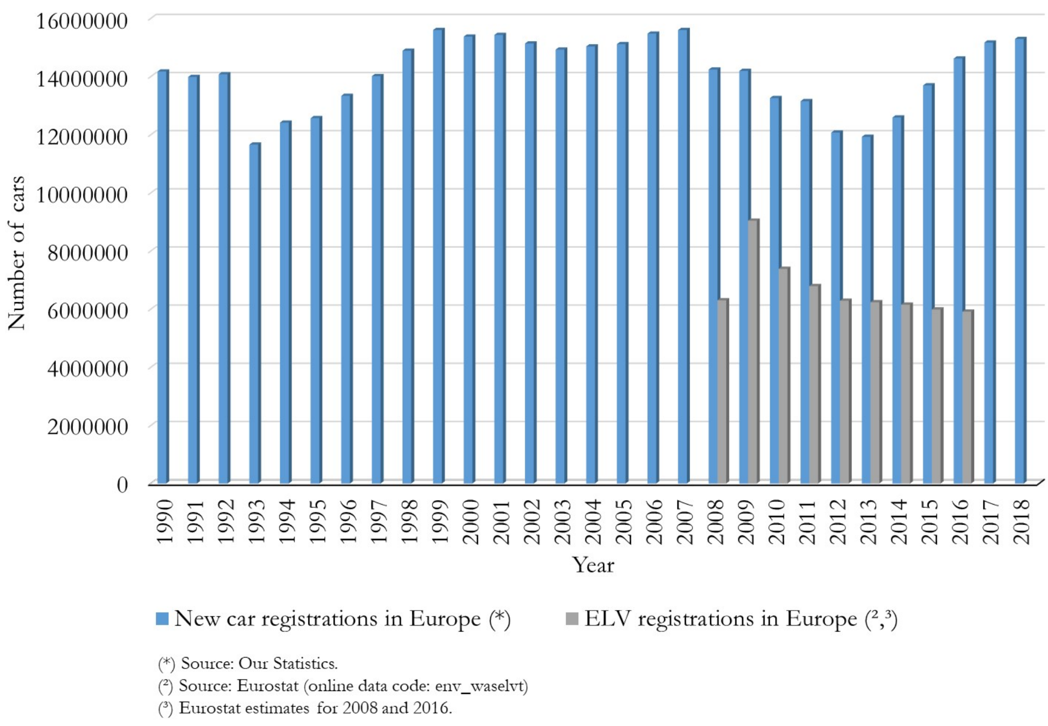

Figure 2.12: New cars and ELVs registration in Europe [75, 33]

The EU ELV legislation, requires 95% of a vehicle to be processed for reuse and recovery and 85% to be processed for reuse and recycling. According to the latest published information by Eurostat [33], the ELV reuse/recovery rate for the EU-28 member states for the year 2016 in an average of 92.6% and the reuse/recycling rate was 86.9% (see Figure 2.13). Still 35%

of the EU-28 nations are below the target of 95% reuse/recovery of ELVs, where as only 14% of the EU-28 states are below the 85% of reuse/recycling target. The OEMs are economically responsible for the complete recyclability of vehicles, including the end-of-life treatments, recycling, and recovery operations [52].

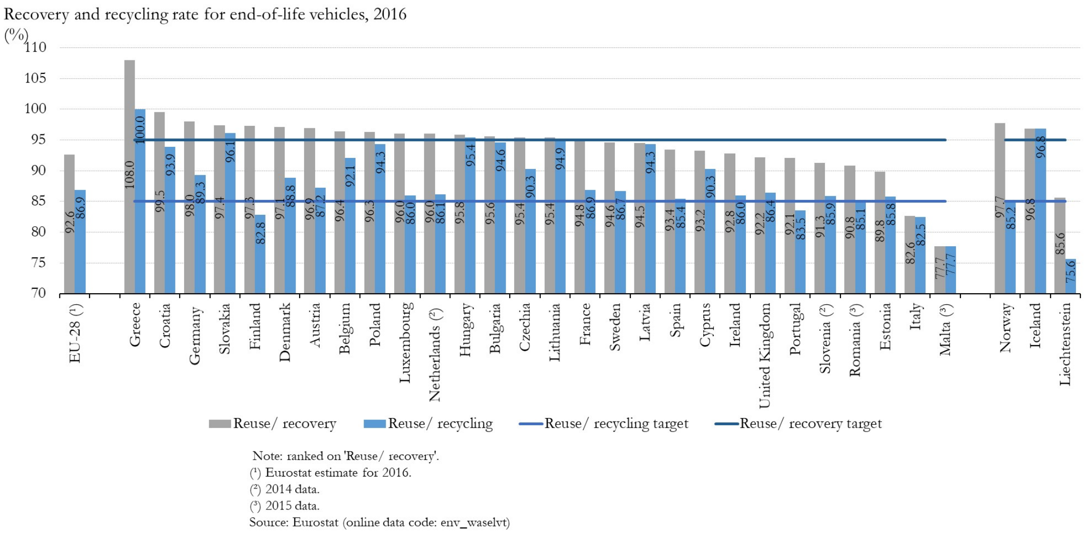

Figure 2.13: ELVs recovery and recycling rate of ELVs in 2016, modified by the author [33]

As stated by Hatzi-Hull; the material composition of the ELVs in the year 2015 (see Table 2.1), had around 12% of plastic waste [40]. The content of the plastics in the ELVs in year 2015, is close to the amount of plastics used in the vehicles produced in the early 2000s'. The 75% of metals from the ELV are completely recycled and to achieve the ELV Directive targets from 2015 (see Figure 2.11), at least 10% of the used plastics to be recycled. Looking further deep in to the plastics types and their content in an ELV in year 2015 (Table 2.2), the contribution of PP was 40%. The PP waste from the ELVs are high quality raw material for the PP recycling grades, which can be used in new automotive application after up-scaling the performance by compounding process.

The review of the ELV Directive by December 2020 [41], might increase the recycling rate of the ELVs, which is currently lower than the recovery rate. Recycling of the high volume of plastics from the ELVs can highly contribute in achieve the targets of the ELV directive. On the other hand, the plastics waste generated from the ELVs is good quality raw material sources for the recycling and usage of this recycled material in new car parts manufacturing

Material	Weight %
Ferrous Metals	66
Non-Ferrous Metals	9
Plastics	12
Tyres	3
Glass	2
Batteries	1
Fluids	1
Textiles	1
Rubber	2
Others	2

Table 2.1: ELV material composition in 2015 [40]

is highly feasible.

Material	Weight %
PP	40
ABS	7
PC	4
PA	8
PU	11
PE	5
PVC	7
Epoxy	1
Others	17

Table 2.2: Plastics material composition in an ELV - 2015 [40]

The cars recently produced with higher plastic composition after their life time (approximately in 11 years), have large plastics waste content in the ELVs in year 2030. Table 2.3 shows the estimated material composition of the ELV in 2030. The share of plastic waste in 2030 from the ELVs are 3.6% more compared to the number of 2015 (shown in Table 2.1). Recycling of the plastics from the ELVs will be crucial to achieve the ELV Directive targets and at the same time help the OEMs use more recycled materials in new cars from the used cars, reducing the footprint of their products.

Material	Weight %
Metals	72.9
Polymers	15.6
Elastomers	3.9
Glass (and Ceramic)	3
Liquids	3.1
Natural Materials	0.4
Others	1.1

Table 2.3: Estimated ELV material composition in 2030 [36]

2.5 Automotive Plastics - Recycling Models

As previously mentioned, the key principle for the emission reduction and environmental pollution by plastics, is the circular economy, where the products and materials are circulated at their highest values all the times. In the technical cycle, this implies that the plastic parts used in the cars, after their end of life-cycle can be either reused when possible and then recycled. There are different kind of recycling (Figure 2.14) [20]:

- Chemical recycling
- Mechanical recycling in open loop
- Mechanical recycling in closed loop

2.5.1 Chemical recycling

In the chemical recycling process, the polymer chain structure is broken down into individual monomer level or other hydrocarbon products than can be used as feedstock for producing polymer materials again. The chemical recycling of plastics is of more interest, only if the mechanical recycling of the waste is not suitable or feasible. This technology is of high focus and under development.

2.5.2 Open Loop Recycling

According to definition of EllenMacArthur Foundation, in the open loop mechanical recycling process the polymers are kept intact, but due to the degradation or material property

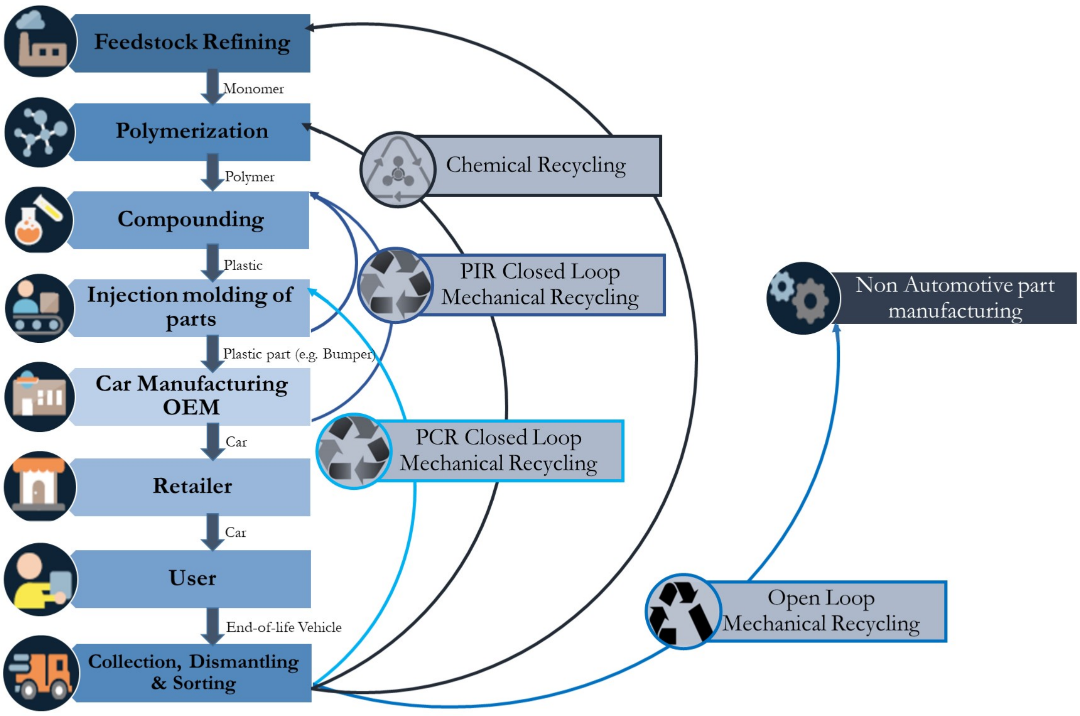

Figure 2.14: Types of plastics recycling [20], modified by author for automotive industry

changes in the materials, the recycled materials require application with lower demands[20]. As explained by Sofie Huysman & Dewulf et al., in open loop recycling process for example 1 kg of plastics waste from the household after recycling, either mixed with a certain percentage of virgin plastic or compounded and used for producing parts with different low demand applications[72]. The simple definition is, the plastics recycled in a open loop process will be used for different purpose than their original application.

Example: In Volvo XC60 the tunnel console that runs down the centre of the front seats is made from renewable fibres and plastics from discarded fishing nets and maritime ropes [81].

Another good example in automotive sector is RIALTI [66], a private Italian company specialized in supplying recycled PP compounds filled with glass fibers (GF) or talc for different automotive application. The source of raw material for producing the PP recycled compounds are selected industrial scraps, mainly of textile origin [66].

2.5.3 Closed Loop Recycling

The closed loop recycling, which is mostly mechanical recycling, is the most value-preserving loop, as defined by EllenMacArthur Foundation[20]. In this process, the quality of the material, after recycling, is maintained at the similar level by cycling the materials either into same applications (example: from bumper to bumper) or into new applications, where the quality requirements are similar. The source for the recycling is the post-consumer ELV waste, which follow several processing steps and the recycled materials are used in new vehicle manufacturing. The other source of raw material for the closed loop recycling is the post industrial waste. The scraps and plastic waste created during the production of the car parts or components can be collected and recycled. This recycled plastics are used in the production of new car parts.

Example: In Clio IV (2016), the car bumpers and wheel arch liners consist mainly of recycled PP from ELVs [36].

The European Commission has initiated several LIFE projects related to end-of-life vehicles and tyres waste, under which the ICARRE95 (France) project Industrial Platform Demonstrator to achieve 95% recycling of the "end-of-life vehicle" was conducted with collaboration between Renault, vehicle dismantling network INDRA, plastics recycler Synova, metals recycler Duesmann and more than 50 additional contributing parties [31]. Close loop recycling of plastics is also a term used in Renault automotive industry as sustainability program for recycling and reusing plastics in the automobile manufacturing [36]. The project was established to develop new feasible technologies to increase the recycling of the materials for ELV, which are usually inadequately or not recycled, especially plastics, foams, textiles. The focus was to demonstrate the economic and environmental viability of the closed loop recycling within the automotive industry [79].

In Figure 2.15, the closed loop recycling process of PP and other polymer materials by Renault from the ELVs is represented. The first and the foremost step of the recycling process is the collection of the ELVs and dismantling of the ELVs to retrieve the substantial amount of the value embedded in the ELV parts. Through close collaboration between INDRA,

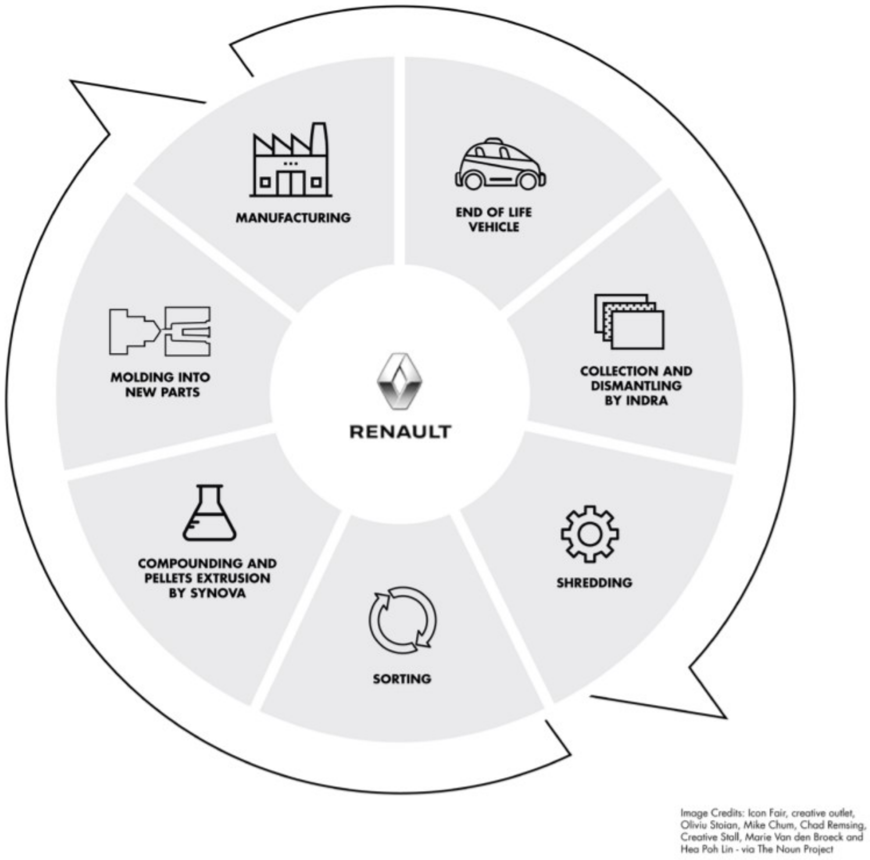

Figure 2.15: Renault - Closed loop PP recycling [79]

Renault and its contributors, significant improvements were achieved in the quality and collection effectiveness and dismantling processes at the organisation's network of 400 vehicle dismantling centres throughout the country [31]. In the dismantling stage, recyclers recover the fluids and remove the usable parts and components of the vehicle. These include lead-acid batteries, wheels and tires, steering columns, front and rear fenders, radios, engines, starters, transmissions, alternators, and select plastic parts and components in and out of the vehicle—based on the parts condition and market demand [74]. The larger plastic parts like bumpers, dashboards, car door panels, instrument panel etc. are collected, depending on the part condition, separately for recycling process. In the ELV dismantling stage, both the material recovery and spare parts recovery is performed. The recovered parts are resold for export or to other national market as second hand parts. the tyres are used mainly for energy recovery and recovered plastics materials are marketed to the recycling industry [43]. The plastic parts are shredded and then sorted out, due to combination of different plastics types. The separated PP material is then compounded in a twin screw extruder with addition of fillers or additives and made into pellets. SYNOVA, as expert in compounding of recycled plastics for automotive industry, provided their raw material requirements to be met by both the dismantling and shredding companies [79]. The recycled PP pellets are later used for manufacturing of new PP visible car parts, such as door panels by injection molding process, which are finally mounted on to the new cars.

One more best example for the closed loop recycling of PP in the automotive sector is WIPAG Deutschland GmbH [83], which recycles both post-industrial waste such as stamp-outs or scraps and post consumer plastic waste such as parts from the end-of-life vehicles. Through a complex recycling process, which includes shredding, delamination, density separation and electrostatic separation, the production waste of bumpers or dashboards are recycled and used again in the production of bumpers or dashboards [73]. The separation of the different plastics used in the bumpers and dashboards is very crucial for recycling process as well as the quality of recyclate.

The bottlenecks of the closed loop plastic recycling process were identified by Vluter et al. [79], based on their research on two case studies (Renault and Lexmark) on closed loop plastics recycling, is shown in Figure 2.16:

The challenges of the closed loop plastics recycling can be grouped into three categories [79] - collection, recycling process and manufacturing with recyclates.

- *Collection of plastic waste* - Currently there are varying developed systems for waste collection and recycling infrastructure globally. In Automotive sector, due to lack of the infrastructure for the ELV collection and dismantling, the plastics recycling is very complicated and mostly the plastic waste ends up as shredded residuals. The parts recovered by the ELV dismantlers and shredders vary depending on the condition, makes, models, and ages of the ELVs processed, as well as the market demand for the particular part and assembly types [52]. The collection process is of high cost aspect, as smaller quantities of waste to be collected from different smaller resources for the recycling process. The post industrial waste from the part manufactures (Tiers) are

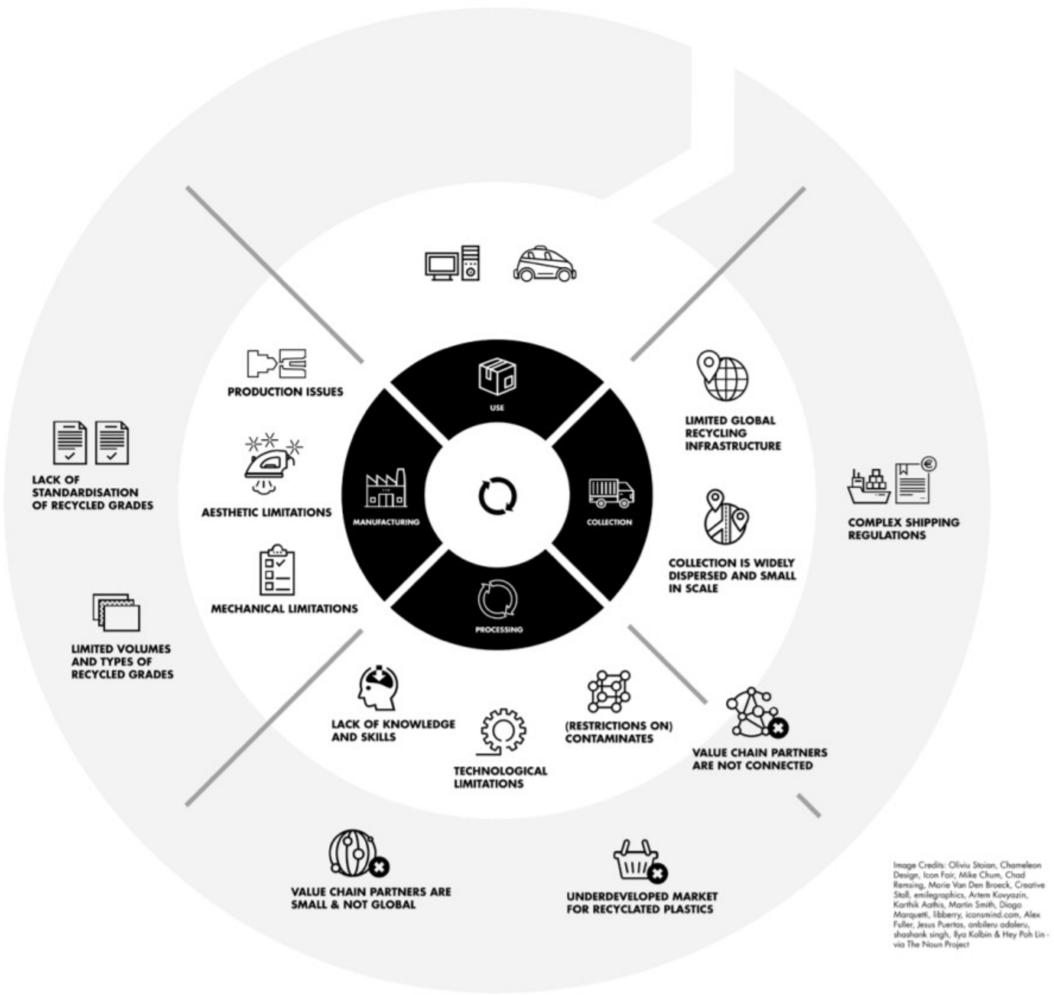

Figure 2.16: An overview of bottlenecks to closing the loop of plastics. [79]

mostly collected and sent to their recyclers or in some cases recycled internally.

- *Processing of recycled plastics* - The market for the recycled plastics is still small, although the technology and business models are developing rapidly. The economic feasibility of using recycled plastics depends mainly on their cost advantages over virgin plastics. The suppliers of recycled plastics are often small and mainly available regionally and not globally unlike the virgin plastic suppliers in the market. This lack of maturity in the plastics recycling industry creates challenges with respect to quality, quantity, price and procurement for companies that intend to use recycled plastics in their new products [21, 41]. The connection between the value chain partners - collection, dismantling, sorting, recycling, compounding and part manufactures are insufficient, which challenges the closed loop recycling process. The lack or knowledge and skills of the value chain partners can often results in poor quality or contamination of the recyclates. For example a batch of PP parts from ELVs can easily be contaminated with PU Foams at the dismantling stage [79].

An important technical limitation is the plastics sorting and high possibility of cross-contamination, which affects the mechanical and aesthetic quality of end product. Different technologies, like near infra-red (NIR) or electrostatic separation or density separation, are available for sorting out different plastics resins [36]. However the biggest problem is the overlapping polymer density ranges, which can easily cause cross-contamination of the recyclate. Also combination of different materials may lead to material loss during the sorting process.

- *Manufacturing parts using recycled plastics* - The biggest draw back of the 100% recycled plastics materials, are their poor mechanical performance, aesthetics, odour while comparing with the virgin plastics. For these reasons mostly the recycled plastics are mixed with virgin plastics or the properties are up-scaled by compounding process, where additives or reinforcement is made to improve the properties. The other challenge is the consistency of the recycled plastics quality, which can highly vary due to variations in the quality of the feedstocks. Due to these mechanical performance, aesthetics and odour of parts made of post consumer (ELV) recycled plastics, their applications are limited to invisible parts in the vehicles and non-interior applications. Another important parameter is the material color, as the colors of the recycled plastics are limited (grey to black). Since most of the automotive parts are black colored, it is advantageous in using recycled grades but using recyclates for lighter or brighter color application is still a major challenge.

  Lack of standardisation of recycled plastics materials cause additional and repeated testing in order to keep up the quality consistency of the recycled plastics. Combining different sources of plastics waste can lead to consistency issues [79]. For most OEMs the material specifications for the recycled plastics and parts made of recycled plastics are still missing and most OEMs and Tiers expect the same material performance for recycled plastics as virgin plastics. Other main challenge is the volume and variety of recycled plastics available in the market for the automotive applications. .

2.6 Recycled Plastics Market in Automotive Industry

The report of McKinsey&Company [76] states that by 2030 one-third of plastic demand could be covered by recycled plastics due to predicted increase in the mechanical recycling rate up to 22% (12% in 2016, see Figure 1.1). By 2050 it is projected to be nearly 60% of plastics demand covered by production of plastics based on previously used plastics (Figure 2.17).

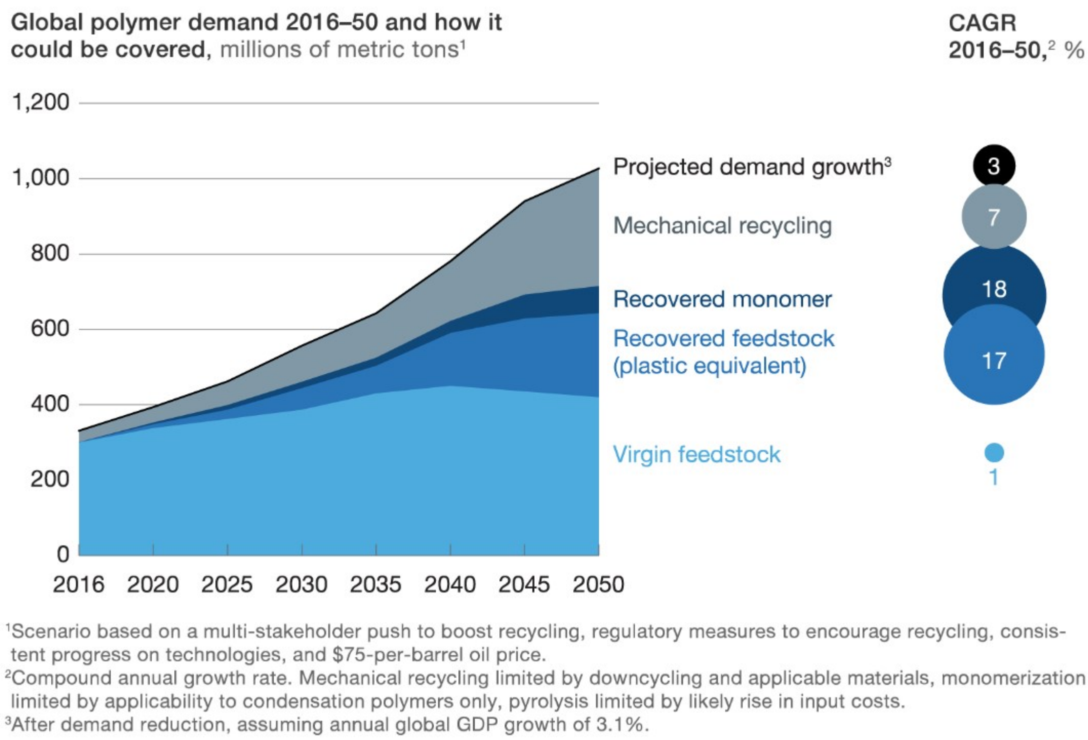

Figure 2.17: Global polymer demand 2016-2050 [76]

Comparison of the global waste polymer flow in 2030 (Figure 2.18) with the global polymer 2016 (Figure 1.1), shows that increased circular plastic usage is predicted by 2030. The wasted collection rate for recycling is estimated to be 50% by 2030, which is a + 34% compared to the 2016. This increase in mechanical recycling and chemical (monomer) recycling, can reduce the landfills (from 40% in 2016 to 18% by 2030) and unmanaged dumps or leakage into the environment (from 19% in 2016 to <1% by 2030) drastically. The cost position of plastics waste based feedstocks - via mechanical recycling, chemical recycling, or reuse through pyrolysis or other feedstock supply - could potentially be very attractive that they could account for two-thirds of the profit-pool growth of the petrochemicals and plastics industry by 2030 [76]. In the future, the plastics waste could be potentially the next source of feedstock advantage for polymer production [76].

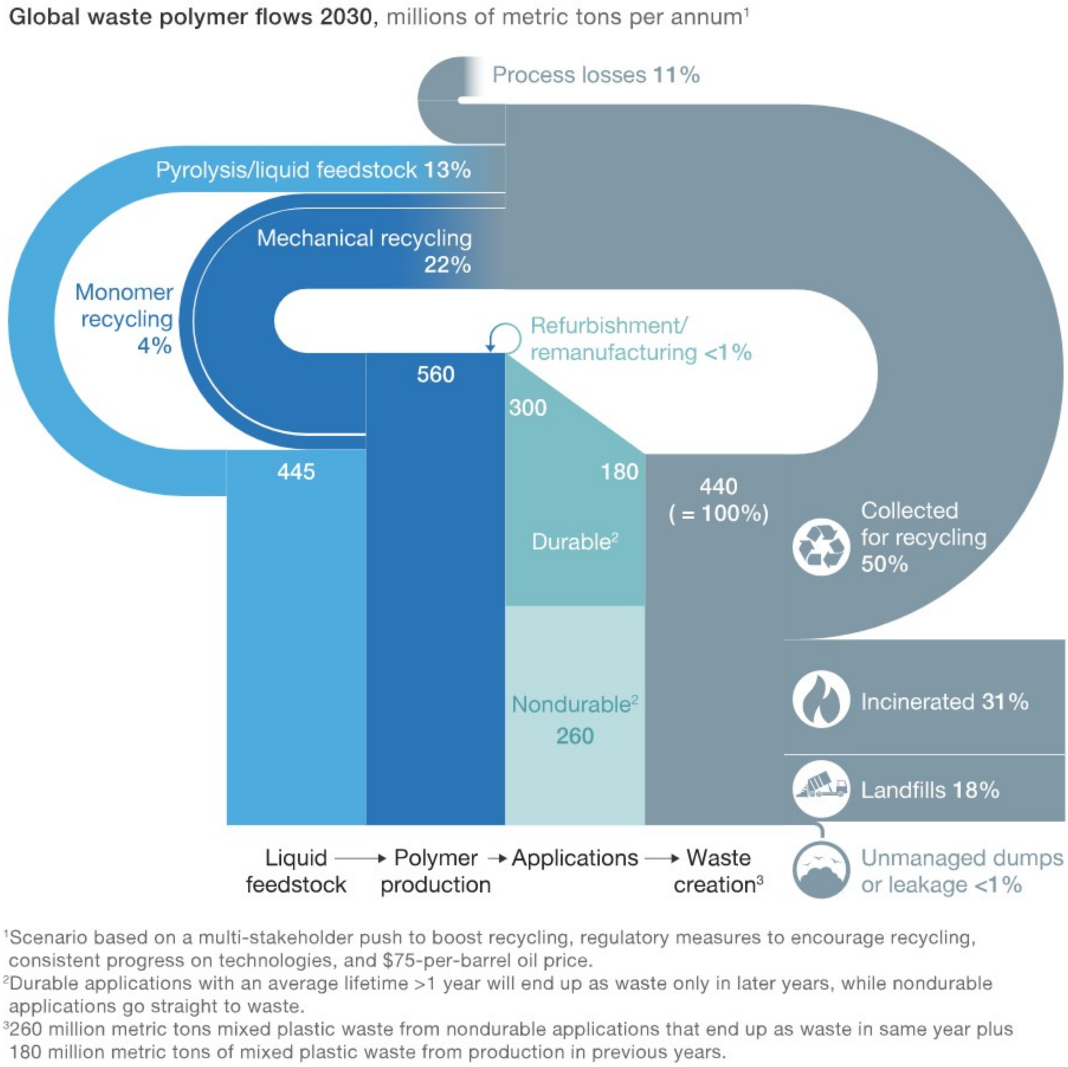

Figure 2.18: Global waste polymer flow 2030 [76]

The growth of recycled plastics usage is expected to increase in all industry segments, due to the increase in circular approach of material usage and sustainability. The market for recycled plastics in the automotive industry was only 8.45% in the year 2017 (Figure 2.19). The largest market for recycled plastics is dominated by the non-food and food contact packaging (total 69%), followed by construction.

Considering the global recycled plastics market by the type of plastic resin (see Figure 2.20), PP material has only 3.76% share, where as polyethylene terephthalate (PET) dominated by 55% followed by high density polyethylene (HDPE , approximately 33%). This due to the fact that both HDPE and PET resins are mainly used in the packaging applications and the recycling of plastics from the packaging industry of high focus in the recent years.

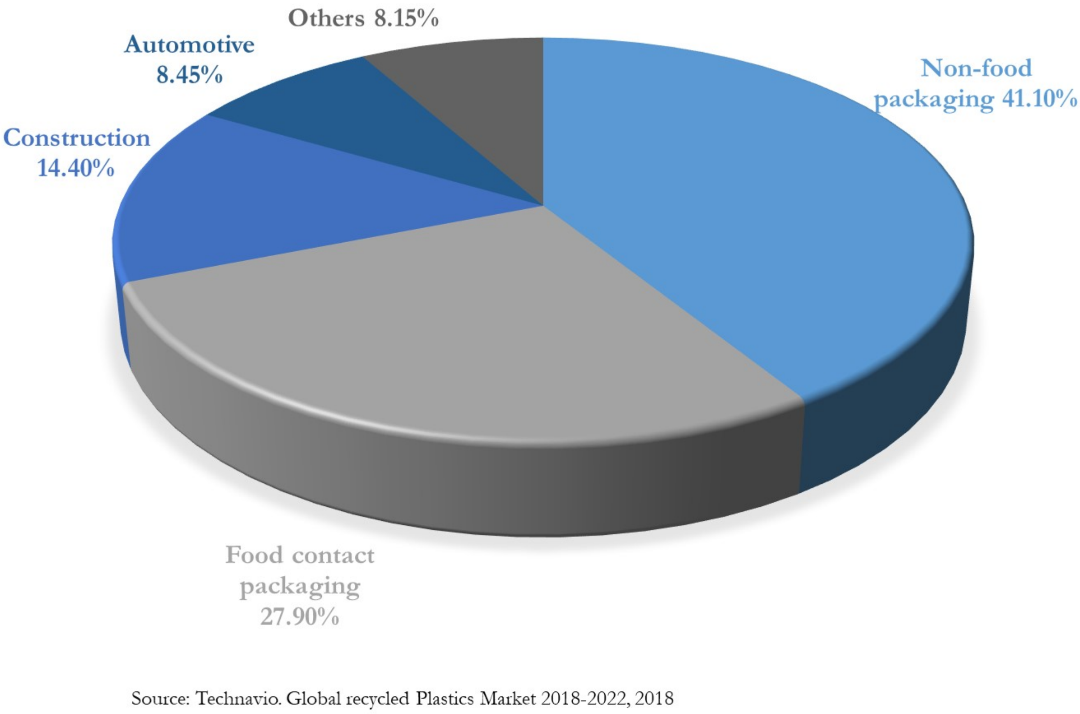

Figure 2.19: Global recycled plastics market by end use in 2017 [46], modified by author

According to the report of PlasticsEurope, in Europe 4 million tonnes of recyclates are produced out of 29 million tonnes of collected post-consumer waste. The plastic recyclates are used in new products in varying end application market (see Figure 2.21) and the share of recyclates applications in the automotive industry is only 3% (Building and construction - 46%, Packaging - 24%, Agriculture - 13%) [63]. The ratio of recyclates to virgin plastics used in the automotive sector is on 2% [63].

BMW Group, an active member of "Circular Economy Initiative Deutschland", has defined group standards to use secondary materials like recycled plastics. In particular BMW i3 uses a large portion of recycled plastics and natural fabrics. Moreover BMW Group has established systems for ELV components and materials and ensure that the raw material are integrated into the raw material cycles for recycling and further use. In order to increase the use of recycling rate BMW is continuously testing new recycling concepts for new vehicle components, using recycled polymer composites and batteries [7].

According to Kilberg [47], Volvo Cars has set several target with respect to recycled plastics and their usage namely; to have at least 25% of recycled plastics in packaging solutions by 2025 and 25% of recycled plastics in every new car from 2025. Volkswagen Group (VW) reuses their plastics waste from production, logistics, technical development and workshops to produce high-quality materials [80]. Daimler stipulates a certain minimum share of recycled plastics in the production of new Mercedes-Benz cars, mainly to meet the European ELV Directive targets [17] and also to reach their company's target - new vehicle fleet to be CO_2- neutral by 2039 [69]. For example, the new A-Class vehicles, consists of 118 components (total weight of 58.3 kg) partially made from recycled or renewable raw materials [69].

Groupe Groupe Renault has taken commitments to approach the circular economy of the vehicles, by extending the components and materials life. They have implements successful systems to recover the materials from ELV and transform them to supply the production of new vehicles [38]. FCA according to their sustainability report [34], supports increased usage of renewable and recycled materials in new products. The usage of recycled polymers and elastomers are significantly lower than usage of recycled metals and FCA is taking efforts to increase more recycled plastics usage. FCA promotes the use of recycled plastics in their design requirements [34].

Considering the recent sustainability reports of major OEMs in Europe, a clear trend of increase in the usage of renewable and recycled plastic materials can be seen mainly to fulfill the ELV Directive requirements and secondly to achieve their own sustainability targets.

According to the ACEA & CLEPA, currently the recycled plastics can be find non-visible application like - wheelhouse arches liners (fender liners), carpets, starter battery tray, engine covers, support for bumpers, etc.[2]. Plastic closed loop recyclers have developed their own technologies to improve the quality of the recyclates and promote the usage of the recycled plastics in interior and visible area applications. Volvo cars, presented the possible vehicle components where the recycled plastics can be used [47]:

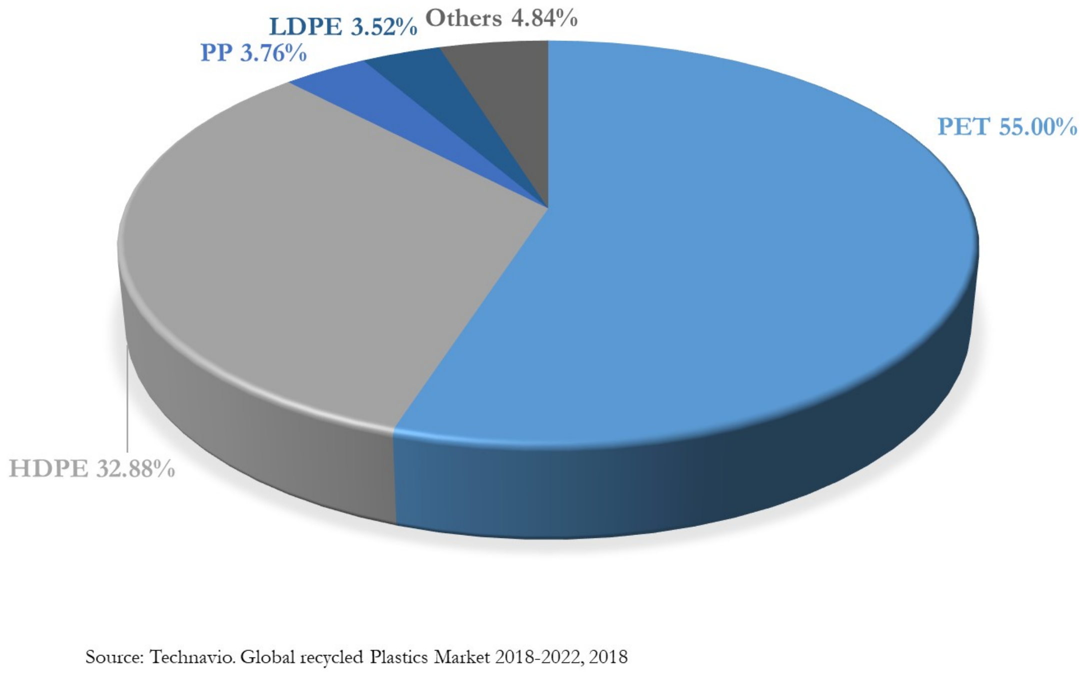

Figure 2.20: Global recycled plastics market by plastics type in 2017 [46], modified by author

- Powertrain - Fuel and Urea-tank, clips, air filter box, electronic control module, fan shroud, expansion tank, air intake, engine cover, belt cover, casings
- Body & Trims - Carpets, heavy layers, floor fillers, Trim pillars, Luggage panels, load floor, Door panel carriers & pockets, Headliner, Panels, hardbacks, ski hatch, laminate, Glovebox, defrost duct, subframe, concealing, panels, end covers, Tunnel panels, carriers, Surface textile, HVAC casings & ducts, Lamp casing front & rear, Cleaning system container, pipes, Front and rear door carriers and multi functional brackets, Exterior cappings, Inner tailgate, Air guide, frame, panel, Sill moulding, Bumpers, HWAS –heat water air separator, plenum, Underbody panels, wheel house liners
- Electrical & Chassis - Equipment boxes, Wire harness, channels, Loud speaker brackets, antenna box, subwoofer casing and channels, casings

OEMs are continuing to increase the share of the recycled plastics in their new vehicles, to the meet the stringent requirements of the automotive industry [2].

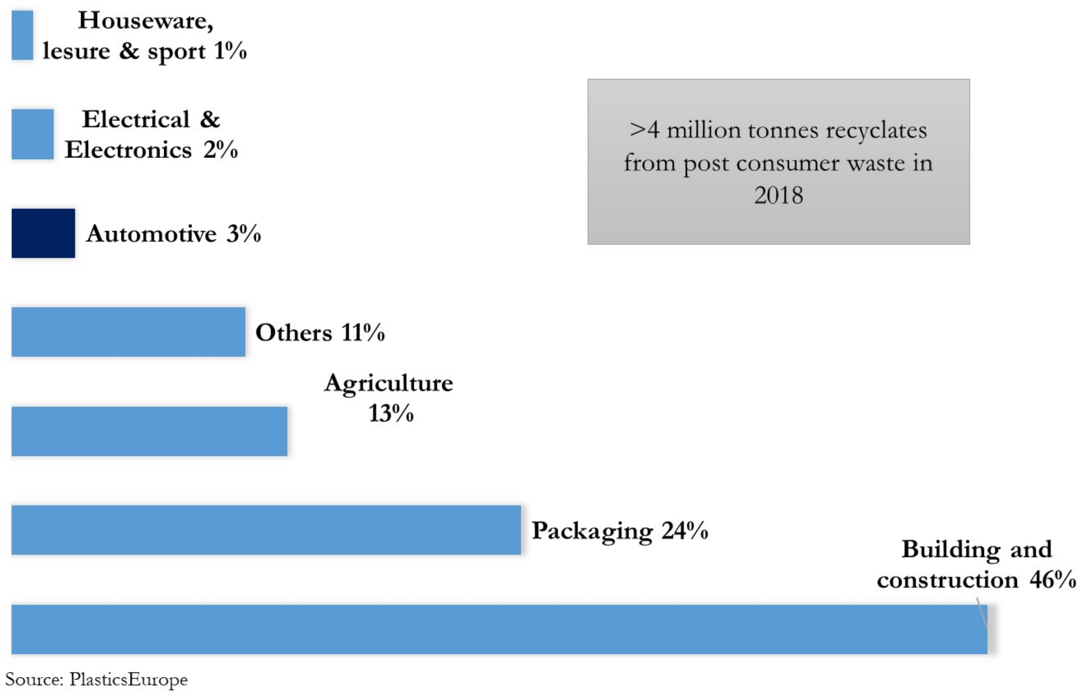

Figure 2.21: Plastics recyclates usage EU28+2 in 2018 [63], modified by author

2.7 Key Findings - Literature and Market Research

The market and literature research study on the closed loop recycling of plastics and the usage of the recycled plastics in the automotive industry led to following key scientific findings:

- The four main future trends of the automotive industry (autonomous driving, electric vehicles, connected mobility and shared mobility), required new light weight material solutions (more plastics and their composites) in order to fulfill different requirements, namely increased fuel efficiency, reduce CO_2 emissions, recyclability.
- The usage of plastics and their composites are expected to increase in the future cars (upto 20%), replacing some of the metal parts.
- The global demand for plastics produced from mechanical or chemical recycling of the plastics waste is projected to be nearly 60% of total plastic demand by 2050.
- The changes in the ELV Directives and the targets of the European new plastics strategy demands high recycling rate of the plastics instead of plastics waste ending up in

energy recovery or landfills. Moreover the European new plastics circular economy strategy insists the OEMs to use more recycled plastics in the new vehicles.

- The ratio of registered ELVs to new registered passenger cars in Europe is still very low, which reflects the need for better and stricter ELV management in EU countries.
- OEMs are setting sustainability goals, to reduce the carbon foot print of their vehicles by increasing the usage of more sustainable materials - recycled plastics and bio based materials. The demand for using recycled plastics in the new vehicles is increasing.
- One of major challenges of using recycled plastics in the automotive industry is availability of recycled plastics with high quality standards in the market is low.
- Currently the recycled plastics are restricted to only invisible and low performance applications in vehicles.
- Several challenges are involved in closed loop recycling of the automotive plastics. The main challenge is the quantity of plastics retrieved from ELVs and post industrial waste are not high enough, which lowers the economical attractiveness of recycled plastics.
- The wide density variants of plastics and different material combinations used in car parts, lead to loss of valuable materials during dismantling, shredding and sorting process.

The outcome of the literature and market research highlights that the low volume of quality feedstocks available for closed loop recycling makes the recycled plastics not economical for automotive usage. Some feasible solutions are needed to increase the volume of quality recycled plastics for automotive applications. The empirical research is designed to identify feasible proposals to solve the recycled plastics quantity problematic, considering the different aspects like - material/part specifications, design for recycling, challenges in closed loop plastics recycling.

"Today's linear economy is a straight line, no matter how efficient you are. If you make a car with less materials, if you make a car using less energy, you're still using stuff, you're still consuming materials. Whereas within a circular model, from the outset you design in a way whereby that product comes back into the system: the components are recovered, the materials are recovered."

Dame Ellen MacArthur

3 Empirical Research

Scientific research can be a combination of both theoretical and empirical approach. The empirical part of this thesis is structured in a way to compare the primary data gathered with the theory and mainly to answer the research question defined in Chapter 1.3. The two main methodologies used for the primary data collection are experts interview and experts workshop. The business analysis tools - SWOT, PESTLE, Porter's 5 Force are used in this research to get a clear understanding of the closed loop plastics recycling business in automotive industry. The design for recycling rules were identified through experts workshop. Interview with experts from the plastics and ELV plastics recycling industries were performed to compliment and validate the findings and data gathered through the literature and market research (summarized in Chapter 2). In the following sections the used empirical methods, analysis tools and the procedures are detailed.

3.1 SWOT Analysis - Experts Workshop

Strengths, weaknesses, opportunities and threats, abbreviated as "SWOT" is a micro economical tool commonly used methodology to analyse a business's strengths and weaknesses and identify opportunities and external threats that could affect the business. The strength and weaknesses are internal factors; opportunities and threats are external factors [39]. The SWOT method is relatively easy to understand and perform by identifying the important factors of each four areas [39]. According to Leigh [45], SWOT analysis can be used for business strategy development, industrial analysis (for contextualizing market opportunities), situation analysis and scenario planning (for considering probable, possible and preferred future scenarios).

Schoenmayr [70] in his research work, analysed the SCOT (strengths, challenges, Opportunities and Threats) of recycled plastics in the automotive sector (see Figure 3.1) and the conclusion of his study is that the recycled plastics have significant benefits than the virgin plastics when considering the ecological and economic aspects, although the quality of recyclates offer room for improvement. The quality to performance ratio and quantity to volume ratios of the recycled plastics are considered to be one of the big challenges. The increasing price of the recycled plastics is seen as a threat [70]. The SCOT results of Schoenmayr [70] focused on recycled plastics in general and their usage in automotive sector.

In this research, the SWOT analysis, focusing only on the closed loop circular economy model in the automotive industry, was done based on the six-step process of conducting the SWOT analysis defined by K. H. Silber & Dessinger et al. [45], which is as follows:

- Step 1 - Defining the group of stakeholder
- Step 2 - Convening the focus group about the scope and background
- Step 3 - Identifying and categorizing the SWOTs
- Step 4 - Analysing SWOTs
- Step 5 - Synthesizing the SWOTs

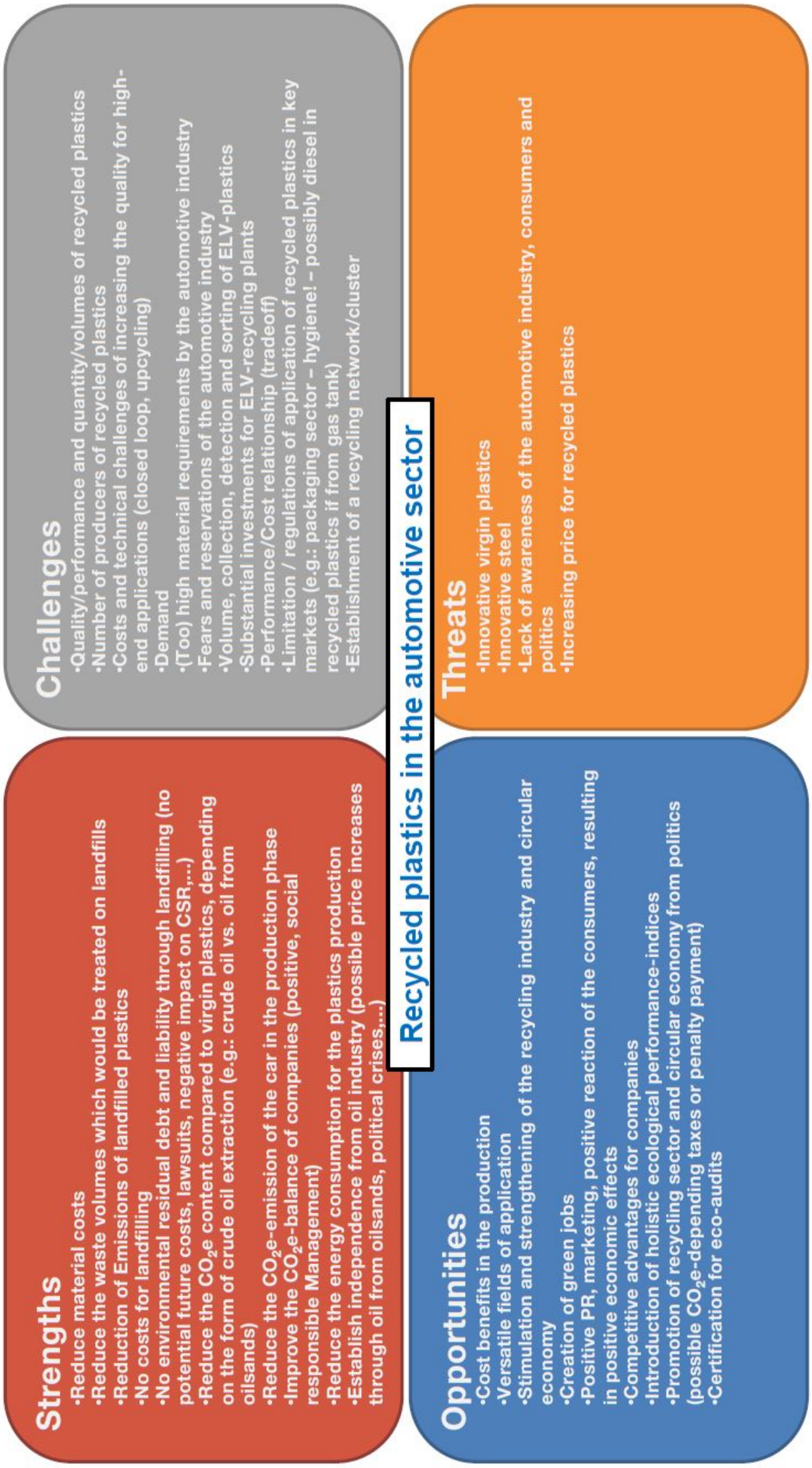

Figure 3.1: SCOT analysis - Recycled plastics in automotive sector [70]

- Step 6 - Interpreting the findings

The SWOT analysis workshop was carried out with several experts from the Automotive and Circular Economy Solutions (CES) department of Borealis AG. The chosen experts have several years of experience in their respective branches, mainly Polyolefins for automotive market and recycling of Polyolefins. The workshop was conducted in two sessions at Borealis Innovation Headquarters in Linz, with two smaller groups of experts. The first session involved four experts from CES studio and two experts from Automotive Marketing department. The second workshop session involved several technical experts and application engineers from Automotive Marketing department, working closely with the OEMs. During both the workshop sessions the gathered information through market research, literature review and expert interviews by the author was not presented to the experts in order to promote the out-of-box thinking of the participants. The background information about the workshop, closed loop circular economy model and the rules of the workshop session was clearly communicated. Then the participants were given sufficient time to identify the SWOTs individually and then the results were presented by each participant individually. During the SWOT presentation, the identified points were categorized. Analysis and synthesis of the collected data from both the sessions were done by the author. The results (shown in Chapter 4.1) of SWOT analysis was presented to the participants in an extra session and the validation of the result was performed.

3.2 Macro-Economic Analysis - PESTLE

PESTLE is an acronym that stand for Political, Economic, Social, Technological, Legal and Environmental factors (Figure 3.2). PESTLE analysis is a business analytical tool used to monitor the macro-environmental factors that may have a profound impact on an organisation's performance or a new business. For a clear understanding about the situation and related internal and external factors of e new business, the PESTLE analysis is often used in collaboration with other business analytical tools such as SWOT analysis (see section 3.1) and Porter's five Forces (see section 3.3) [59]. In order to understand each macro-economical factors of closed loop plastic recycling in automotive industry, the following questions were considered to identity the important influencing factors and their respective consequences to the plastics recycling industry. Through a brainstorming session with Dr. Andreas Gemes, Manager of CES Strategic Project at Borealis, the PESTLE analysis was performed. The three step approach mentioned by Klaus Kerth & Stich et al.[48] for performing the PEST analysis was followed in identifying and documenting the economical factors and their implications.

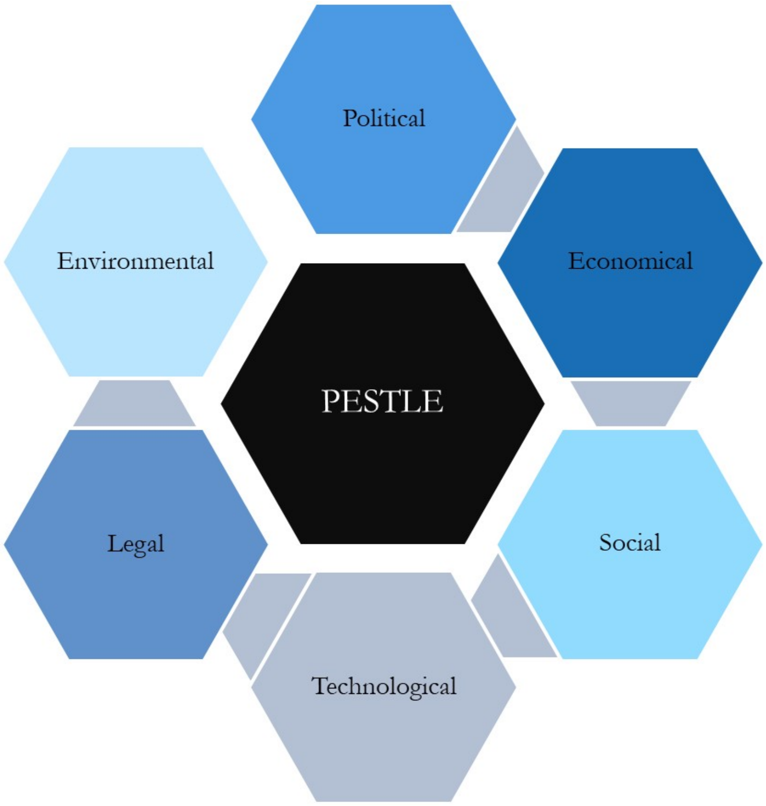

Figure 3.2: PESTLE

- Political factors - Governmental policies that influence the economy or the industry
  - How the European Commission policies are driving the changes in the automotive industry and recycling industry economy?
  - What governmental policies are promoting the usage of recycled plastics?
  - What are the impacts of EU commissions new plastics strategy to automotive industry?
- Economical factors - determinants of an economy's performance
  - How is the price of the recycled plastics in comparison to virgin plastics?

- How the closed-loop recycling can influence the economy of the plastics recycling industry?

- What new jobs and business opportunities can the recycling industry create?

- Is global availability of the recycled materials possible?

- How the economy of virgin plastics manufacturing industry can be influenced/affected by the plastics recycling industry?

- Social factors - social environment of the market, and gauge determinants like cultural trends, demographics, population athletics etc.

  - How the users accept usage of recycled plastics in the new cars?

  - Image of recycled plastics vs. virgin plastics?

  - How the society is accepting the plastics in general?

  - Why OEMs are focusing on increasing recycled materials for new parts production?

- Technological factors - technology developments that may affect the operations of the industry

  - Is chemical recycling a better solution?

  - What are the influences of the Industry 4.0 with respect to post-industrial waste?

  - How cost efficient is the plastic recycling in Automotive business?

  - How effective is the dismantling and sorting technology for mixed plastics waste from ELVs?

  - How advanced is the recycling technology, to ensure the quality requirements of the automotive market?

  - Is maximizing the volume of plastics for recycling from ELVs or post industry scrap feasible?

  - How is the traceability of the raw material ensured in the closed-loop recycling business?

  - Can recyclates fulfill all the material performance same as virgin plastics?

- Legal factors - laws that affect the business environment in a certain country

  - To what extend the ELV directives is influencing the usage of recycled plastics in new vehicles?

- How the REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) regulations can affect the usage of recycled plastics from ELVs in the future new cars?

- Environmental factors - determined by the surrounding environment

  - What are effects of closed-loop plastics recycling industry have on the environment (CO_2 emissions, environmental pollution, climate changes etc.)?

  - How closed-loop recycling can influence the fossil sources or virgin plastics industry?

  - What are the consequences of missing ELVs in the European Union?

  - How the depletion of virgin plastics usage can affect the environment?

The outcome of the PESTLE analysis is presented and discussed in section 4.2.

3.3 Porters 5 Force Analysis

Porter's Five Forces analysis a macro tool for business analysis that helps analyzing the level of competition within a certain industry. As mentioned earlier the SWOT, PESTLE and Porter's Five Forces analysis tools are used combined when starting a new business or when entering a new industry sector or used as a start-up model for analysing the organisation [58, 39]. According to this framework, the state of competition in an industry depends on five basic forces (Figure 3.3) [65]:

- Threat of new entrants - the ease with which a new competitor can enter the market

- Bargaining power of suppliers - the control and power of the suppliers to raise the price or reduce the quantity of goods or service

- Bargaining power of buyers - the power of the customers to change the price

- Threat of substitute products or services - easiness of the customers to switch to an alternative product

- Existing industry rivalry - current competition in the market

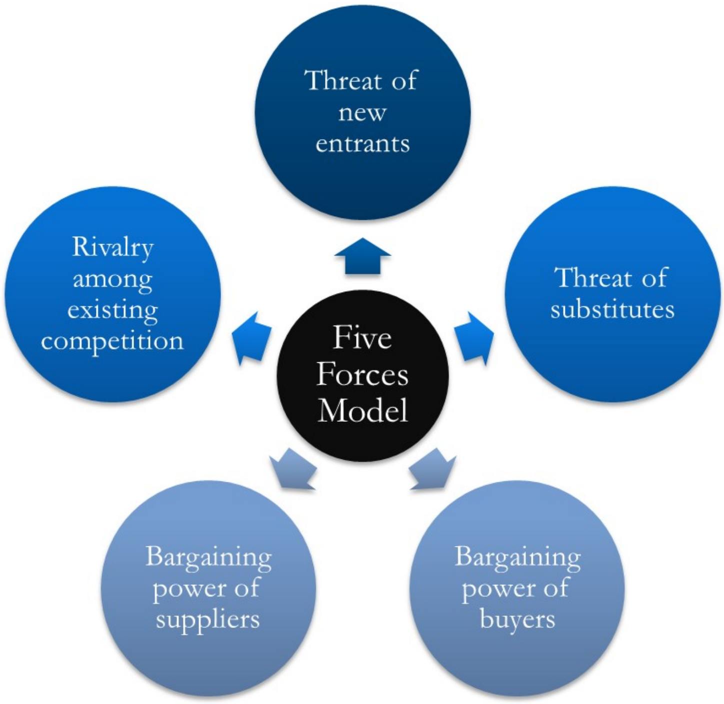

Figure 3.3: Porter's five forces

The attractiveness of the new business or industry and it's profit potential are determined by considering the collective strength of the above mentioned five forces [58]. In this research, to evaluate the attractiveness and potential long term profitability of the closed-loop plastics recycling business in the automotive industry, Porters five forces analysis was performed according to the procedure defined by Klaus Kerth & Stich et al. [48]. Through a brainstorming session with Dr. Andreas Gemes, Manager of CES Strategic Project at Borealis, the Porter's five forces analysis was performed. The steps followed during the Porter's five forces analysis are:

- Step 1: Analysing the closed-loop recycling industry structure The competitive forces - existing competition, supplier power, customer power, substitutes and new entrants, were analysed using quantitative ranking.
- Step 2: Identifying the key rules, chances and risks of the closed-loop plastics recycling industry From the results of five forces analysis, the key rules and logic behind the functioning of the closed-loop plastics recycling business for the automotive sector is identified. Conclusively the possible chances and risks involved in the automotive

plastic recycling branch are analysed.

- Step 3: Defining the measures Considering the learnings from the previous steps, measures are defined for implementation.

3.4 Experts Interviews - ELV plastic recyclers and plastic producer and recycler

To explore the current challenges, technological developments in the closed loop plastics recycling industries and gather reliable data for comparing the results of literature and market study, expert interviews were carried out. The semi-structured interview method, which combines some structured questions with some open-ended exploration of an unstructured interview [82], was used. This interview methodology was used in this research work because the semi-structured interview method is useful when the researcher has some knowledge about the topic and need to explore new issues [82]. According to Wilson [82], semi-structured interview provides the possibility to use probes and spontaneous questions to explore, deepen the understandings, and clarify answers to questions, when working with complex topics.

The procedure and the practical advice on semi-structure interview provided by Wilson [82], was followed during the interview. During the planning phase, the main goals and focus areas for the semi-structured interview were determined. Considering the available data from the literature and market review and required data for further research, a list of standard as well as ad hoc questions were developed (see Appendix A). Through internet research the companies for interview were chosen and contacted. Conducting the interview began with the brief description of the scope, interview topic, data usage and result communication. Before beginning with the interview questions, the interviewees provided a brief introduction about their respective companies and products. The interviews were carried out with experts from companies producing and supplying recycled plastics (mainly PP) for the automotive industry (Table 3.1). The details about the interviewed companies and their products are briefed in Appendix B.

Interviewee Name and Function	Business Area
Nicholas Kolesch Head of Automotive Marketing Borealis AG, Vienna	Polyolefins (PP compound for Automotive Industry, PP and PE - packaging, healthcare,etc.), Base chemicals and Fertilizers
Tobias Klopfleisch Head of Technical Service and Application Development WIPAG, Germany	Open and Closed loop recycled plastics for Automotive Industry
Elena Antonioli Key Account Manager Rialti Spa, Italy	Recycled PP mainly for Automotive Industry

Table 3.1: List of interviewees

3.5 Case Study - PP Materials for BUMPERS

The necessity for larger volume of plastics waste from different sources (like ELVs, Waste Electrical and Electronic Equipment WEEE, etc.) for recycling process was highlighted in the research made by Gallone & Zeni-Guido [36]. Their study estimated an additional loss of 9.5% material, if a batch of bumpers from multiple OEMs of future ELVs were processed in 2030 in the same ways as they are today. Another major complication involved in identifying and sorting ELV plastics is that manufactures in the automotive industry have different material specifications for the same plastic part and it's application. The huge variety of plastics and different grades of materials available in the market for a single application in the car (here for example the bumpers) lead to loss of valuable materials, which can be used in recycling process.

The most commonly used plastics sorting method in the recycling industry, is the separation of plastics by their density differences. Small variations in the amount of fillers (like talcum, glass fiber, carbon fiber, etc.) in the PP compound can highly influence the density of the compound. As mentioned by Vluter in his report [79], Renault for their bumpers may use an unfilled grade of PP, where as a competitor or another OEM might use filled PP grades for bumpers. Due to the variation in the densities the unfilled PP having density <1000 kg/m^3 will flow into the stream for recycling, where as filled PP have density >1000 kg/m^3 will get lost during the material sorting process.

The hypothesis of this research is, that the standardisation of the material specification by the OEMs could lead to reduce the loss of plastic material during sorting process of automobile shredder residue (ASR - a heterogeneous mixture of residuals of ferrous and non-ferrous metals (5-23%), plastics (20-49%), rubber (3-38%), textile and fibre material (4-45%), wood (2-5%) and glass (2-18%) [15]) from the ELVs and hence the quantity of plastics waste from ELVs for recycling can be increased.

Since many different plastics are used for varying automotive parts and applications, the comparison of all the material specifications by different OEMs is not possible. Moreover the OEM material specifications are confidential document between the respective OEMs and their material suppliers. For these reasons, only the PP materials available in the European market for car bumper application, supplied by three top material suppliers - Borealis AG [8], Lyondellbasell [53] and Sabic [68], are compared and analysed in this research.

"The sooner we adapt a genuinely circular economy mind-set, the better: for our own business growth, for the benefit of our customers, and for greater society. It's not good enough to just think about new solutions in the circular economy. We have to actually implement them in practice – because this is what truly circular thinking is about."

Alfred Stern, Borealis CEO

4 Research Findings

Data collected through the empirical research (detailed in Chapter 3), and their analysis, results interpretation are elaborated and discussed through out this chapter. The SWOT and PESTLE analysis are used to identify the internal, external factor influencing the close-loop plastics recycling industry supplying the recycled plastics for the automotive sector. Through Porter's five force model, the competitive forces of this close-loop recycling business was studied. Three experts interviews, which involved experts from ELV plastic recyclers, producer & supplier of recycled PP for automotive industry and one the top three polyolefin suppliers in Europe, added to fill the market and literature research findings gap. The main objective of this study, as previously stated, was to propose feasible solutions to increase the quantity of recycled plastics in the automotive sector through the closed loop circular economy model. Some proposals for improving the sustainable usage of plastics in the automotive sector are presented in the final section of this chapter.

4.1 SWOT - Closed-loop Plastics Recycling in Automotive

The conducted expert workshops, for analysing the SWOT of the closed loop plastics recycling model in the automotive sector, gave varied opinions about this model and several new opportunities to improve the closed loop recycling of plastics and their reuse in the new automotive parts. The data collected from the literature review and information gathered during the two workshops were analysed, synthesized and summarized in 2x2 matrix form, which is shown in Figure 4.1. The following sections details the strengths, weaknesses, opportunities and threats of the automotive plastics waste closed-loop recycling business.

4.1.1 Strengths

The foremost strength of plastics recycled from the waste collected from the ELVs and the automotive post industrial plastics waste is the high quality and high purity of the recyclates. The quality of this feedstocks very high compared to the quality of waste sorted from the post consumer domestic waste. The plastics scraps during the parts production process are properly sorted and stored, thus eliminating the cross contamination of the plastics. In case of ELVs, during the dismantling process the different materials used (like metals, plastics,rubber, wood, glass, etc.) are separated, even color sorted and hence lowers the probability of contamination of the plastics waste. This in addition brings the cost advantage, compared to the plastic recyclates produced from recycling of the post consumer domestic waste. Since the quality expectations and material quality requirements in the automotive industry, this strength of the closed-loop recycling model is seen very crucial. Through the defined sources of waste (PIR - scraps from automotive plastics parts manufacturing and PCR - plastics waste from the ELVs) for the closed-loop recycling process, the consistency of the plastic recyclate quality can be easily achieved.

Moreover the usage of recycled plastics has positive impacts to the environmental, namely reducing the quantity of landfill of plastics waste and mostly importantly lowers the CO_2

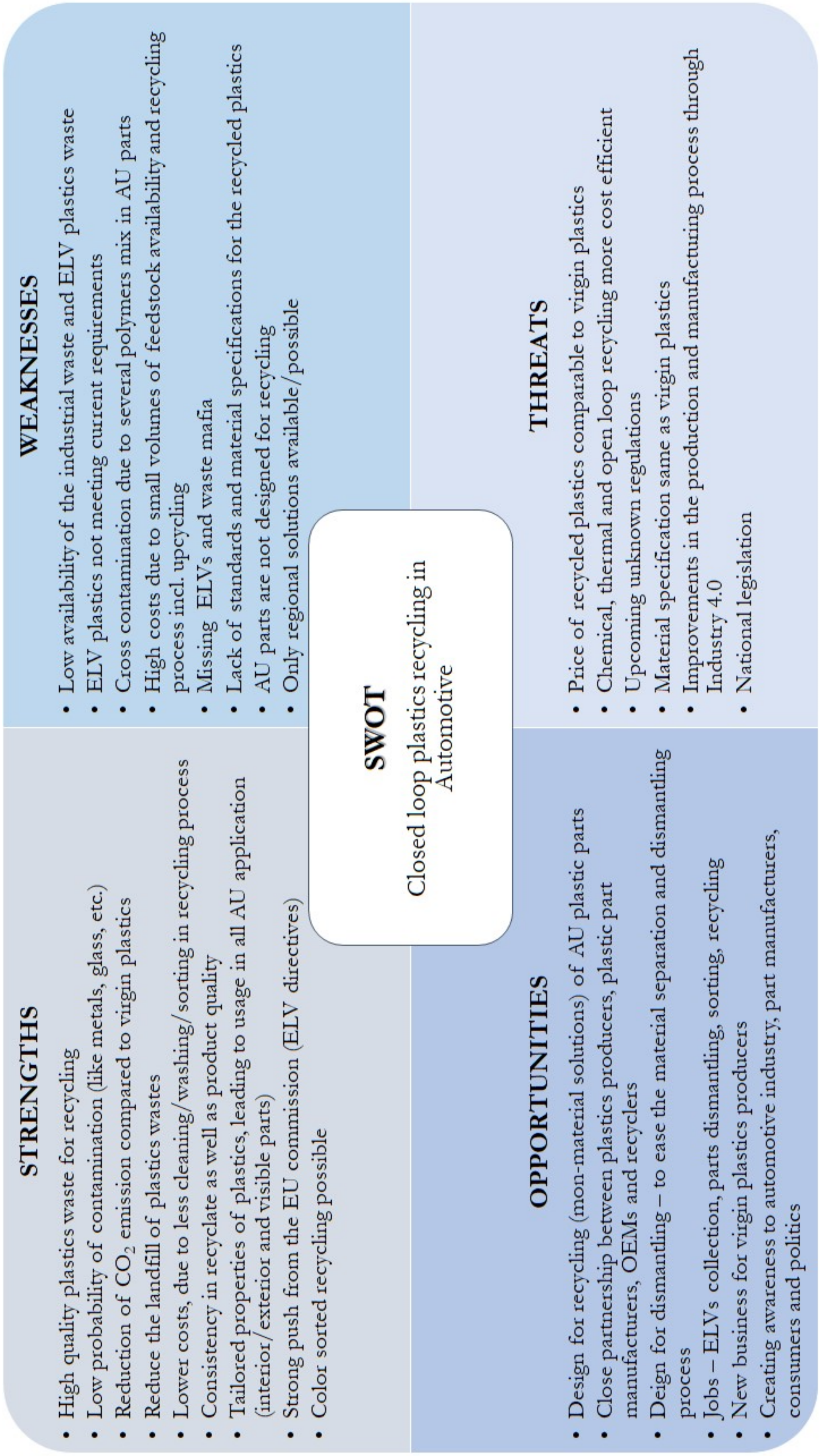

Figure 4.1: SWOT - Closed-loop plastics recycling in automotive sector

footprint. However, during one of the expert workshops, questions and discussions were raised, if the closed-loop recycling model really helps in reducing the CO_2 emissions, since the logistics involved in collection of the ELVs or plastics scraps from different sources and several recycle processing steps (like sorting, washing, compounding, pelletizing, aeration, etc.) could also lead to high energy consumption and CO_2 emissions, which could be at the end comparable to the virgin plastics production. The biggest technical strength of the closed-loop plastics recycling is that, the recycled plastics material can be again used for high end engineering applications. For example the bumpers scraps can be recycled and the material can be used for new bumper applications. Also the purity of the recyclates is high enough, that the material can be used for interior visible parts manufacturing.

The additional strength mentioned is the strong push from the EU Commission, through the ELV Directive and New Plastics Strategy, which promotes the increased recycling rate of the waste from the ELVs, helping the plastics recyclers to increase the volume of feedstock for recycling. This also reduces the amount of sustainable plastic material used for incineration or ending up in landfills.

4.1.2 Weaknesses

The main weakness of the closed-loop plastics recycling business in AU is the low availability of the waste feedstocks from the post industrial and ELV sector. The improvements in the plastics part production process and manufacturing technology is reducing the amount of plastics scraps. In case of the plastic waste from the end-of-life vehicles, due to multi-material solutions (meaning - combination of different polymer types) the plastics cannot be separated anymore and thus lead to material losses. These cross contaminated plastic waste end-up in incineration. The main cause for this material loss is the lack of "design for recycle" thinking in the automotive parts during the part development phase. The missing ELVs in the EU is another main weakness, again affecting the volume of valuable feedstock for the recycling process. Another important technical weaknesses is, that the chemicals or materials present in the ELV plastics are not meeting the current requirements, which could lead to loss of material. The low volume of feedstock for recycling, highly impact the cost of the feedstock and also the price of the recyclates. Additionally, due the lack of standards and material specification for the recycled plastics by the OEMs, upcycling of the plastics through compounding with fillers or additives or reinforcements has to be performed in order to attain the material performance requirements. This process leads to additional cost of the recycled plastics.

Currently only few small recyclers and suppliers are in the market, who provides high quality recycled plastics to the automotive sector but only regionally. The Automotive industry requires the availability of the same quality material globally, which is currently not existing. In order to cover the global availability, huge investment and networking of the value chain is required.

4.1.3 Opportunities

The primary opportunities lie on the technical side of both material and parts for the automotive applications. Both design for recycling and design for dismantling should be considering from the plastics development phase. The front loading of the design for recycling and dismantling thinking by the OEMs to the Tiers is very crucial for a sustainable functioning of the closed-loop plastics recycling process. In case of design for recycling, instead of choosing multi-material concepts for car parts, mono-material solutions should by developed. This will not only ease the dismantling and sorting process easier but also prevent material loss and thus increase the volume of feedstock from ELVs for recycling.

For a successful and economical functioning of the closed-loop plastics recycling business, close partnership throughout the plastics value chain, from the plastic producers, part manufactures (Tiers), car manufacturers (OEMs), customers, recycler (both ELVs and plastics), is very pivotal. Moreover virgin plastic producing companies, making partnership with plastic recyclers have technical, economical and marketing benefits. These closed network could enhance the market availability of high quality recycled plastics, which can be used for high end automotive applications. Consequently this will intensify the usage of recycled plastics in new vehicles and strengthens the whole recycling (ELVs and plastics) industry. The growth of this closed-loop recycling industry can lead to creation of new businesses, startups and new jobs. Another essential opportunity is to promote the awareness about the plastics circular economy among the automotive industry, plastic part manufacturers, consumers and politics. This will be a key to proper disposal of ELVs as well as plastics waste, reusing of plastic parts, integrating more recycled plastics in new car parts and acceptance of the recycled plastics.

4.1.4 Threats

The most important threat to the closed-loop recycling industry is the virgin plastics industry, as virgin plastics are especially cost comparable to the recycled materials, with relatively better material properties. In general the automotive industry consider recycled plastics to be comparatively cheaper than virgin plastics. But due to the low feedstock availability, complex recycling process and upcycling the recyclates, the price of the recycled plastics are very close to the price of the virgin materials. Another salient threat for the closed-loop recycled plastics, is other recycling technologies like chemical recycling or open-loop mechanical recycling or incineration, which is more cost efficient. The technological developments in the chemical recycling and mechanical recycling of plastics waste from non automotive sector could in the near future fulfill the material and quality requirements of the automotive industry. In fact, the usage of glass fiber or carbon fiber filled usage in the cars are increasing due to their light weight with very good mechanical performance, but from recycling point of view they are not suitable for mechanical recycling.

On the other hand most of the car manufactures have no specified material requirements for the recycled plastics and instead they expect the recycled plastics to have same performance as virgin plastics. This lack of awareness and knowledge about the properties and performance of recycled plastics can diminish the usage of recycled plastics in new vehicles. An additional threat is the development in the production or manufacturing processes, e.g. INDUSTRY 4.0, which can drastically reduce the amount of production scraps (post industrial waste). The upcoming unknown regulations and national legislation of the EU countries in plastics waste handling are also considered to be additional threats for the closed-loop recycling industry.

4.1.5 SWOT - Summary

Reviewing the outcome of the SWOT analysis clearly reflect that the closed-loop recycled plastics in automotive have a considerable advantage concerning the purity, quality and consistency of the recycled material compared to the open-loop recycled plastics. Even though the ecological benefits of closed-loop recycled plastics exist, the economical aspects are significantly lower than virgin plastics. The obvious weakness is the low volume of quality feedstock available for a profitable recycling business and lack of material specifications for the recycled plastics. The front loading of design for recycling and dismantling are considered as main opportunities to increase the volume of recycled plastics in automotive industry.

4.2 PESTLE

The important macro-economical factors that could influence the close-loop plastics recycling business were brainstormed by answering the questions mentioned in section 3.2 and with the help of information gathered through expert interviews (section4.4), market and literature studies. The identified critical factors, shown in Figure 4.2, are briefly discussed in the following subsections.

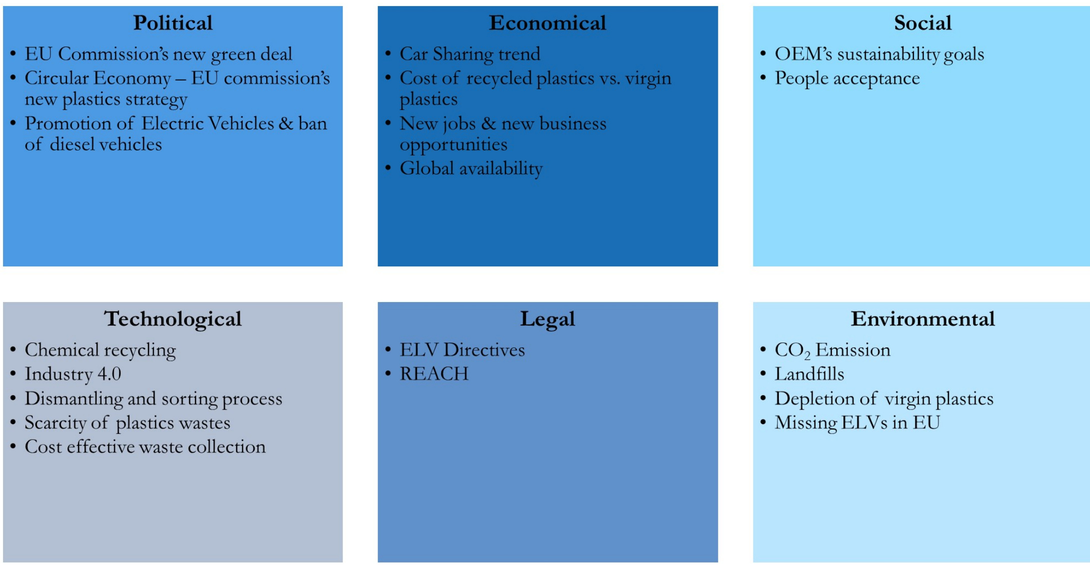

Figure 4.2: PESTLE - Closed-loop recycling of plastics in AU

4.2.1 Political Factors

EU Commission's new green deal

The new European Commission's green deal [30], published in December 2019, support and accelerate the new circular economy action plan, which will include a sustainable products policy to support the circular design of all products. The circular economy action plan will focus particularly on sectors such as textiles, construction, electronics and "plastics", which are highly resource-intensive [30]. The new circular economy action plan prioritise reducing and reusing materials before recycling them. This will also include measures to motivate the businesses to offer, and to allow the consumers to choose, reusable, durable and repairable products [30]. The EU Commission will consider the legal requirements so that a deeper cooperation across the value chains and hence boost the market for secondary raw materials with mandatory recycled content (for instance for packaging, vehicles, construction materials and batteries). For ensuring cleaner secondary materials for the business, EU Commission will propose new EU model for waste collections and stop the export of waste outside the EU. These policies of EU will lead to higher use of recycled plastics in the new vehicles and the use of the waste from the ELVs.

Circular Economy – EU commission's news plastic strategy

The new plastics strategy of EU commission promotes the circular economy model in all application sectors, including automotive. The use of more recycled or bio-based materials are highly promoted. The OEMs are promoting use sustainable materials in their new cars and reduce the CO_2 foot print.

Promotion of Electric Vehicles and ban of Diesel Vehicles

The E-vehicles are highly promoted and restriction of using diesel cars are getting stricter. This is driving the development of E-mobility, where plastic materials play a critical role in reducing the weight of car and thus increasing the mileage of the vehicles. The higher share of plastics in the new cars, will lead to larger volume of waste from the ELVs after their life cycle. To meet the ELV recycling rate target, the maximum possible amount of plastics in the ELVs must be recycled in the future.

4.2.2 Economical Factors

Car sharing trend

The trend of declining car owners due to the increase in the car sharing trend can have an impact on the quantity of vehicles produced per year, which could consequently lower the quantity of waste of plastics from the ELVs for recycling. The ownership of the shared vehicles belongs to the service providers or the OEMs, which have a positive effect on the ELVs collections, reusing and recycling of the value materials from those ELVs.

Cost of recycled plastics vs. virgin plastics

The cost of the recycled plastics especially for engineering applications, like automotive parts, are comparable to the cost of the virgin plastics due to the complex steps involved in the recycling process. But the buyers expect the cheaper price for the recycled plastics than the virgin plastics. The attractiveness of the recycled plastics shrink due to the lower quality-price-ratio compared to the virgin plastics for engineering applications.

New jobs and new business opportunities

The circular economy strategy in the plastics industry can pave way for new business models and new jobs. In case of automotive industry, the ELVs collection, dismantling and sorting of valuable recyclable materials in an efficient manner can create new business and job opportunities. Also this can increase the business of the plastics and other recycling industries which could consequently create new work possibilities.

Global availability

The global availability of the plastics materials and parts for the car manufactures with the same quality standards is of high importance. Meeting the global availability requirement of the car industries for the recycled plastics business is not easy, as in virgin plastics, due to different regulations and infrastructure present in different nations globally.

4.2.3 Social Factors

OEM's sustainability goals

OEMs are showing special interest in reducing the carbon footprint of their vehicles and they are setting high sustainability goals besides the targets set by the EU commission. As part of their sustainability goals, OEMs are introducing more recycled plastics or bio-based plastics and more natural materials in the new vehicles. This factor is the main driver for the increase in the demand for recycled plastics in automotive industry.

People acceptance

The acceptance of the products made out of recycled plastics by the consumers is of great significance for the growth of plastics recycling industry. People proclaim a higher level of acceptance for recycled materials and contribute their part for the environmental protection. This acceptance by the public is vital not only for the consumer products or packaging industries but also for the automotive industry.

4.2.4 Technological Factors

Chemical recycling

Currently the mechanical recycling process is dominating the plastics recycling industry. This trend might change in case of automotive plastics, as chemical recycling will be necessary to recycle the plastic parts due the usage different plastics material combination and increased carbon/glass fiber reinforced plastics for reducing the weight of the vehicles.

Industry 4.0

The fourth industrial revolution "Industry 4.0", which is developing rapidly in all industrial sectors has also impact in plastics processing process. The developments in the plastics processing technologies, together with the introduction of Industry 4.0 not only reduces the part development, set-up and start-up times but at the same time reduce the amount of production scraps. The production scraps from the part manufacturing companies is also one of the main sources for the closed-loop plastic recycling industry. Minimizing the scrap production can negatively impact the volume of feedstock for the plastics closed-loop recycling industry.

Dismantling and sorting process

Proper dismantling and sorting of the car parts from the ELVs or disassembling and separation of each components from the production scrap of automotive parts is predominant for the recycling process. If this process is not performed in the specified way, the chances of cross contamination in the recycled plastics are very high. The awareness, knowledge and technical resources for both ELV recyclers and Tiers, who manufacture plastics parts or components or modules for cars, are very important.

Scarcity of plastics waste

The scarce availability of plastics waste with high quality and purity for recycling is one of the biggest threat. The plastics waste loss from ELVs occurs due to lack of design for recycling of the automotive plastics parts. The missing ELVs also impact the reduction in volume of plastics waste for closed-loop recycling. Increasing the volume of good quality of plastics feedstocks for recycling and hence increasing the recycled plastics use in the automotive segment can take off the closed-loop recycling business to a larger scale.

Cost effective waste collection

The price of the high quality recyclates are comparable to the virgin plastics due to the complexity in the process and mostly importantly due to the high costs involved in each process steps (waste collection, sorting, shredding, cleaning, compounding). A cost effective waste collection system, both for ELVs and post industrial scraps, is essential to reduce the price of the recycled plastics.

4.2.5 Legal Factors

ELV Directives

The ELV Directive is the major driving force behind the circularity in the automotive sector. Their main objective to reduce the environmental impact of the ELVs by proper disposal and reuse or recycle of the materials from the ELVs is extending the growth of both ELVs and material recyclers. The closed-loop plastics recycling business can highly contribute in attaining the minimum reuse and recycling rate of 85%. Increase in the recycling rate of ELV Directive by the EU Commission can be advantageous for the recycling industries.

REACH

REACH aims at ensuring high level of protection to environment, human and their health's [3]. Moreover REACH promotes alternative methods for hazardous substances assessment, as well as free circulation of substances within the internal market [3]. Chemicals or substances which were allowed in the plastics or plastics parts or components of the cars manufactured in the past or today, might not be allowed anymore by REACH in the far future. This could lead to restriction of using plastic parts from old cars for recycling and using them in new cars.

4.2.6 Environmental Factors

CO_2 Emission

The circular approach of using the plastic materials not only in automotive segment but in all industries will highly contribute to the reduction of CO_2 emissions (as shown in Figure 2.9).

Landfills

The closed-loop plastics recycling aid in preventing the sustainable materials ending-up as landfills or polluting the environment or polluting the oceans.

Depletion of virgin plastics

The increasing demand for the mechanically or chemically recycled plastics for varying application can lead to depletion of demand for the virgin plastics, which are mainly based on fossil resources.

Missing ELVs in EU

There is huge gap between the newly registers vehicles and yearly registered ELVs in European countries. The missing ELVs or so called 'unknown whereabouts' are some where in the globe causing the environmental pollution, due to improper treatment and recycling of the materials from those ELVs. Diminishing the number of unknown whereabouts can positively impact the quantity of materials for recycling.

4.3 AU Closed Loop Plastics Recycling Industry Structure - Porter's Five Forces

The main goal of this 5 forces analysis, was to understand and to identify the competition among the closed-loop plastics recycling industry and most importantly the long-term prof-

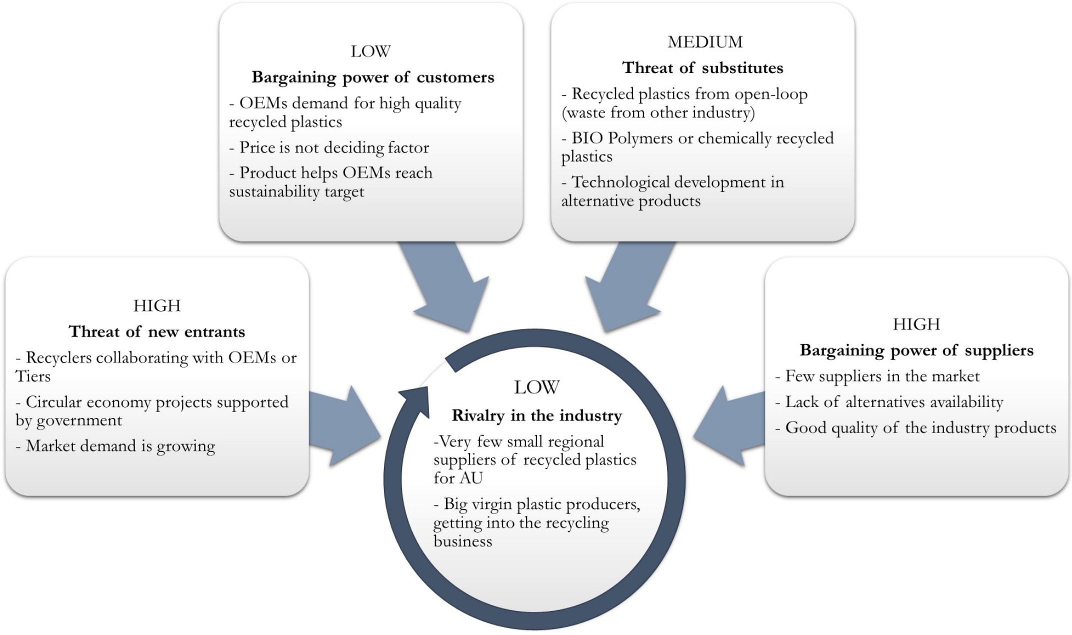

Figure 4.3: Closed-loop plastics recycling industry's structure

itability of the business. All the five forces, shown in figure 3.3, of the closed-loop plastics recycling for the Automotive industry were assessed considering the gathered literature and market information. The outcome of the five forces analysis is diagrammatically presented in figure 4.3. The following sections describes the five forces in detail.

4.3.1 Rivalry in the industry

The competitive situation within the recycled plastics manufacturing and supplying industries is currently low, due to the presence of only few regional producers and suppliers of recycled plastics for the automotive industry. Since only small growing companies are involved in closed-loop plastics recycling from ELVs are available in the market and the demand for the recycled plastics is growing for the automotive applications, the rivalry among those small suppliers can grow in the future. Moreover big virgin plastics suppliers are acquiring the plastics recyclers or stepping into chemical recycling or collaborating with plastic recyclers, which are the sign of growing rivalry in the plastics recycling business.

- BASF - BASF SE published about the investment of €20 million into Quantafuel, a specialist for pyrolysis of mixed plastic waste and purification of pyrolysis oil, headquartered in Oslo, Norway [6].

- Borealis - Borealis acquired Ecoplast Kunststoffrecycling GmbH in 2018, additional to mtm plastics GmbH and mtm compact GmbH, one of the largest European producers of post-consumer polyolefin recyclates in Germany [11].

- LyondellBasell - Two key projects were announced in 2018 to focus on circular economy. LyondellBasell and SUEZ went into a joint venture to acquire Quality Circular Polymers (QCP), a premium plastics recycling company in the Netherlands. In July 2018, LyondellBasell signed an agreement with the Karlsruhe Institute of Technology (KIT) in Germany to advance chemical recycling of used plastics [54].

- SABIC - SABIC announced its ground-breaking project to pioneer the production of certified circular polymers using a feedstock from mixed plastic waste and hence contribute to closing the loop on re-utilizing plastic waste [67].

- Total - Acquired Synova, a French leader in manufacturing high-performance recycled polypropylene for the automotive sector in 2019 [78]

4.3.2 Threat of new entrants

As market demand for the recycled plastics in the automotive industry is growing, there is high potential for regional plastic recyclers, supplying recycled plastics to the automotive market, to grow bigger through their know-how and technical infrastructure. Also the OEMs and Tiers are making co-operation with the plastics recyclers, which could introduce the plastics recyclers to enter the automotive market. The main barrier that could prevent the new entrants, is that the material quality requirements for the recycled plastics is so high, that the recyclers cannot offer the material that fulfill all the OEM requirements.

4.3.3 Threat of substitutes

The chemically recycled plastics could be the biggest threat for closed-loop recycled plastics for the automotive applications. As described already several plastic manufactures are developing and investing in the chemical recycling of plastics waste technology. Additionally the open-loop mechanically recycled plastics and bio polymers can be the threat to the closed-loop recycled plastics.

4.3.4 Bargaining power of the customers

The Tiers and OEMs demand high quality recycled plastics that can be used for new automotive parts and thus attain their sustainability goals. But the availability of such quality recyclates are limited in the market. The presence of only few suppliers for high quality recycled plastics and non availability of alternative materials in the market that can fulfill the OEM requirements, reduce the bargaining power of the buyers.

4.3.5 Bargaining power of the suppliers

The power of the suppliers to influence the price of the recycled plastics is high, as the only few suppliers are available in the market. Plastics recyclers use plastic waste from both ELVs and the scraps from the part manufacturing industries, which must be disposed by the industries. Due to the unavailability of the alternatives and high risks of contamination in the post consumer domestic waste, the closed-loop plastics recyclers can offer good quality recyclates at higher prices to increase the margins.

4.3.6 Key Findings

The analysis of the automotive closed-loop plastics recycling branch structure (Figure 4.3) shows that the competition among industry is currently low due to existence of only very few companies in the market. But this situation can change due to strong involvement of big virgin plastics producers entering into both mechanical and chemical recycling business and increasing the collaboration with OEMs, Tiers and recyclers. The chemically recycled plastics is considered to be biggest alternative to closed-loop recycled plastics. The performance and quality of post consumer recyclates from domestic waste are currently unable to meet the requirements of the OEM standards. But the improvements in the recycling and sorting technologies can change this situation and make the PCR material as an alternative to closed-loop recyclates. The OEMs require higher volume of high quality recycled plastics to meet their sustainability goals and reduce the carbon footprint of the new vehicles, irrespective of the price of the recycled plastics. The need for high quality feedstock for the recycling industry extends the supplier bargaining power of the suppliers. The existing small ELV recycler and plastics recyclers can grow in the market. The strategy for success could be partnership of big virgin material producers with smaller recycler (for utilizing the technologies and infrastructure) and at the same time collaboration with the OEMs and Tiers (for utilizing the large volume of quality feedstocks for recycling). For reducing the costs of recyclates, new business models for waste collections and waste sorting is required additional to the implementation of design for recycling and dismantling of automotive plastics parts during the development stage.

4.4 Expert Interviews

The expert interview questions (Appendix A) were framed into four main groups, mainly to understand the challenges in the plastics recycling industry concerning the automotive applications and get the experts proposals and perspectives about increasing the usage of recycled plastics in the automotive sector. The outcome of the interviews are summarized in the following sections.

4.4.1 Challenges

The foremost challenge in using the recycled plastics for automotive applications, is to fulfill the high demanding material requirements for recyclates by OEMs. Most OEMs lack specifications for the recycled plastics and instead the same performance as virgin polymers is expected at cheaper price [50, 5]. One technical challenge in using the recycled plastics is meeting the odor and emission requirements for the automotive interior parts [5]. The advances in the compounding, recycling, sorting technologies allow the plastics recycling process to retain the quality requirements and its consistency. To prolong raw material traceability and feedstock quality, creating awareness and developing suitable systems together with the feedstocks suppliers is a key.

In case of closed-loop recycling, the odor, emission, contamination are not considered to be a challenge due to purity and high quality of the feedstocks. Due to the high purity of the closed-loop recyclates, the material can even be used for visible interior parts [49]. The lack of motivation and awareness by the OEMs and Tiers to utilize the potentials from the plastic production scraps and waste from ELVs, is also seen as a weakness.

The post industrial waste, either from the automotive plastics industries (closed-loop) or other plastics processing industries (open-loop) are considered to the best suitable source of feedstock currently, due to its high purity level and low contamination risks [5, 49]. The plastics waste from ELVs are most suitable for automotive low end applications, due to the material properties. Even though the polymers loose their performance over time due to degradation, the up-scaling of the recyclates can be done during the compounding stage by addition of fillers or reinforcements or additives can boost the performance of the recycled materials. The compounding step is inevitable during the plastics recycling process, mainly for recyclates used in engineering applications. The post consumer domestic waste are not considered to be the best suitable raw material, due to high contamination risks. All though from the volume point of view the PCR is considered to be cost effective with acceptable consistency in quality.

4.4.2 Plastic Part Design

The multi-material design concept, for example different plastic types used for dashboard application, lead to additional steps in the material separation process and also can cause loss of material. In case of bumpers, the material loss is low, because no material combinations are used. This loss is low only if bumpers scraps from one particular OEM is recycled together. In case of ELV bumpers, where different bumpers from different vehicles and car manufactured are mixed, the percentage of material loss is higher, due to varying PP compound densities.

The color of plastics used in automotive parts are mainly black, which is advantages and disadvantages to the recycling process. The recyclates are mostly grey or black, which can be easily further processed into parts that are black. The disadvantage of the plastic parts with carbon black masterbatch, is the detection problems caused during the material sorting in the recycling process. Near infra-red (NIR) technology is the widely used system for sorting the plastics and this system cannot detect parts that uses carbon black pigments. In that cases either dual detection technique or alternative black pigments which is NIR detectable should be used.

4.4.3 Proposals for improvements

Some of the proposals by plastics recycling industry experts to increase volume and usage of recycled plastics in the automotive are:

- Creating or re-valuating of the OEM material specifications for recycled plastics, instead of using the virgin material specifications also for recycled materials.
- Integrating design for recycling and design for dismantling during the plastics part development phase.
- Mixing of recyclates with the virgin plastics to meet the material requirements
- Avoiding multi-material design and implementing mono-material design of parts can ease the dismantling, sorting and recycling of the materials from ELVs.
- Creating awareness among the Tiers and OEMs to sort and separate the production scraps and utilize the value of the post industrial scraps.

4.4.4 Recycled plastics in Automotive

The market for recycled plastics in automotive industry is growing rapidly, similar to other market segments. The plastic suppliers and recyclers are expanding their production capacities to be competitive in the market. The feedback from the interviewees regarding the reason behind the increase in demand for recycled plastics in automotive sector, is mainly due to the OEM's sustainability targets and reduction of CO_2 footprint of the vehicle by using more recycling solutions. The usage of recycled materials in new vehicles add some marketing benefits to the OEMs. The advances both in open and close-loop plastics recycling process are paving the way for the usage of recycled plastics even in the interior and visible part application. Previously the recycled plastics were used only for non-visible applications in the cars. Moreover through compounding process the performance of the recyclates are up-scaled and in applications the parts are manufacture by 100% recycled material. The other main reason mentioned is cost. Mostly customers expect very cheap price for the recycled plastics. But the price of the recycled plastics vary depending on the area application in the vehicles and in most cases the price is comparable or slightly lower than the virgin polymers.

4.5 Passenger Cars PP Bumpers Recycling - Case Study

The car bumpers are important structural components, designed to absorb energy and thus prevent physical damage to the front and rear ends of an automobile during collisions. The bumpers are designed to protect the hood, trunk, frame, fuel, exhaust and cooling system as well as the protection of the safety relevant equipment, such as parking light, headlamps and tail-lights during the low speed collisions [71]. All passenger cars and most minivans worldwide uses the bumper system with three main components - a plastics fascia, reinforcing bumper beam and energy absorption system [71]. The important requirements for a bumper fascia are the design, style, easy fabrication, light weight, paintability and recyclability of the used material. Developments in the plastic materials and processing technology has in fact reduced the wall thickness of the bumper fascia with better performance. The bumpers are generally made out of plastics, either unpainted or painted same as the car body color, and some times decorative elements like chrome or aluminium insert are integrated [36]. Among automotive plastics, bumpers is one of the best applications which utilizes the circular economy model effectively, as bumper can be reused before they are recycled.

The car bumper fascia (both front and rear) are one of the largest plastics parts in vehicle, with high plastic volume consumption. According to M.P. Luda & Guaratto et al., the bumper contributes to 7%-12% of the total plastics fraction in the vehicle [57]. The most commonly used material for bumper production is Thermoplastic olefins (TPO), which are blends of polypropylene (PP) with ethylene-propylene rubber (EPM) or ethylene-propylene-

Figure 4.4: PP front and rear bumper of passenger car - unpainted

diene monomer (EPDM). The front bumpers (Figure 4.4) are mainly made from unfilled TPO, utilizing the toughness and elasticity of the TPO whereas the rear bumpers (Figure 4.4) are often manufactured from talc filled TPO to reduce the production or material cost [57]. The mineral fillers are used not only to reduce the material cost rather also to improve the mold shrinkage and stiffness of the bumpers. Other polymers like Polyurethane (PU), Polycarbonate (PC), Acrylonitrile butadiene styrene (ABS) are also used for bumper production. The total weight of the bumpers in a passenger car is approximately 9 kg [16]. The weight of the front bumpers is usually heavier than the rear bumpers. The bumper weight is dependent on the passenger car size and type, for example in SUVs the weight of bumpers is high compared to a small or medium sized vehicle.

Manufacturer pool/Manufacturer	EU Market Share (%)	Average mass (kg)
Toyota-Mazda	6	1351
Renault	11	1281
PSA-Opel	17	1269
Nissan	3	1370
Ford	7	1411
Kia	3	1356
Average		1392
FCA-Tesla	6	1300
VW Group	23	1413
Hyndai	4	1318
BMW	6	1589
Volvo	2	1760
Daimler	6	1620

Table 4.1: EU new passenger vehicles weight in 2018 [42]

The average mass of the EU passenger cars manufactured in 2018 is 1390 kg (see Table 4.1), according the ICCT report [42]. In Europe, 15.1 million new passenger cars were registered in 2018 [1], as shown in figure 2.12. The average age of the passenger cars in European Union, according to the ACEA is 11.1 years [1]. From the figure 4.5, it can clearly seen that within the European countries the average age of the passenger cars varies between 6.4 years and 17.3 years. The age of the car are lower in the central and western European countries than the eastern European countries. This is a clear indication of different number of ELVs registered and varying volumes of ELV plastic waste generated in every year different European countries.

Considering the average vehicle age of 11.1 years (Figure 4.5), the 15.1 million new passenger vehicles registered in Europe will attain their end-of-life in 2029. If we assume the average share of plastics in the cars produced in 2018 as 15%, around 208.5 kg plastics waste will be generated in 2029 by each ELV. Assuming that the 15.1 million new cars from 2018 are registered as ELVs in 2029, a total of 3.1 million tonnes of plastics waste will be generated from the ELVs.

While focusing on to the bumpers, to predict the amount of plastics used for the production front and rear bumpers, the new passenger cars registered in 2018 by segment in the EU should be considered. Figure 4.6 shows the percentage share of small-, lower-,upper-medium sized vehicles, multi-purpose vehicles (MPV) and sport utility vehicle (SUVs). As previously mentioned, the bumper weight is dependent on the size of the vehicles, for calculation of the plastic bumper fascia weight the car segment cannot be neglected. In 2018, the total share of SUVs is 35%, which is around 5.3 million vehicles. Whereas the share of small sized vehicles is 29%, that is around 4.4 million vehicles. In the calculations, average bumper weight of 10 kg/car is considered for small-, lower-, upper-medium and luxury car segment, where as for MPV and SUV 13 kg/car is assumed. This gives a total of approximately 172000 tonnes of plastics materials from the front and rear bumpers of 15.1 millions new passenger cars registered in Europe in year 2018.

The recycling process steps involved in the PCR bumpers (collected from ELVs) recycling at WIPAG is shown in figure 4.7. The bumper dismantled by the ELV recyclers are pressed

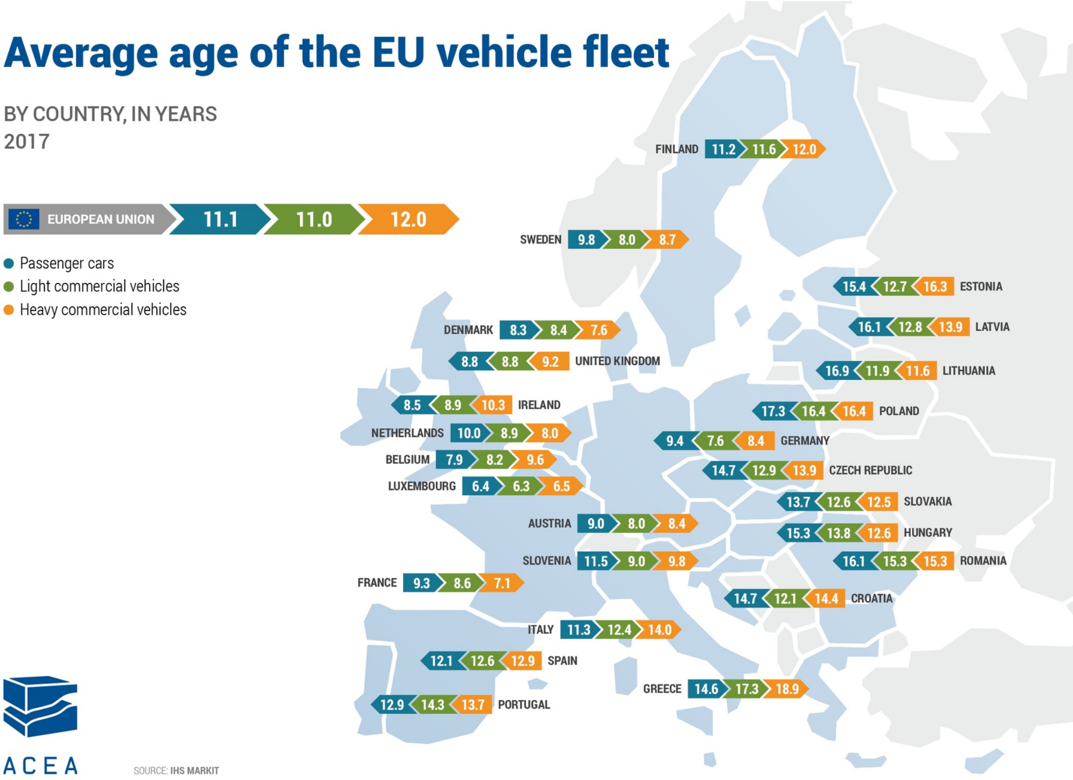

Figure 4.5: Average age of the EU vehicle fleet by country in 2018 [1]

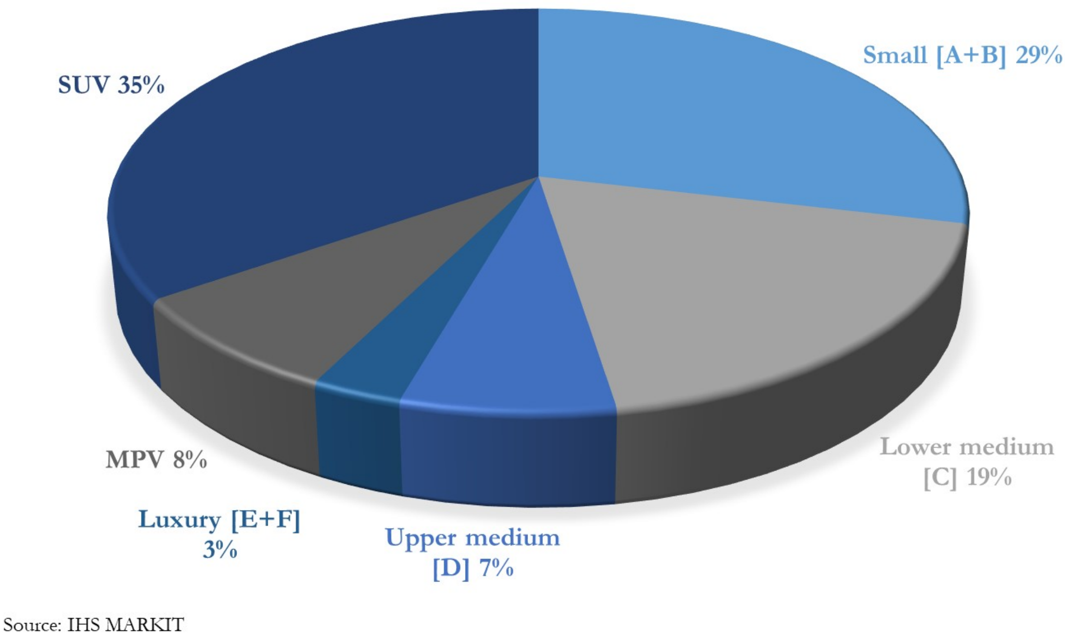

Figure 4.6: New passenger cars by segment in the EU - 2018 [42], modified by author

into bales, mainly for space saving during the transportation. The collected bales from different ELV recyclers are shredded and de-metallized before the sorting of material takes place. Density separation technique, where the shredded material is fed into a floating tank with water and PP material with density lower then 1000 kg/m³ is separated. The heavier materials settle down in the water bath and thus the contaminants are removed. The extracted pure PP materials is compounded in a twin screw extruder, with additional of virgin PP material or additives or fillers to improve the material performance. The compounded melt is passed through fine filter mesh to remove possible contamination and finally pelletized into granules. This recyclates can either used as blend with virgin PP for new high end car parts or without blending for low end applications in new vehicles.

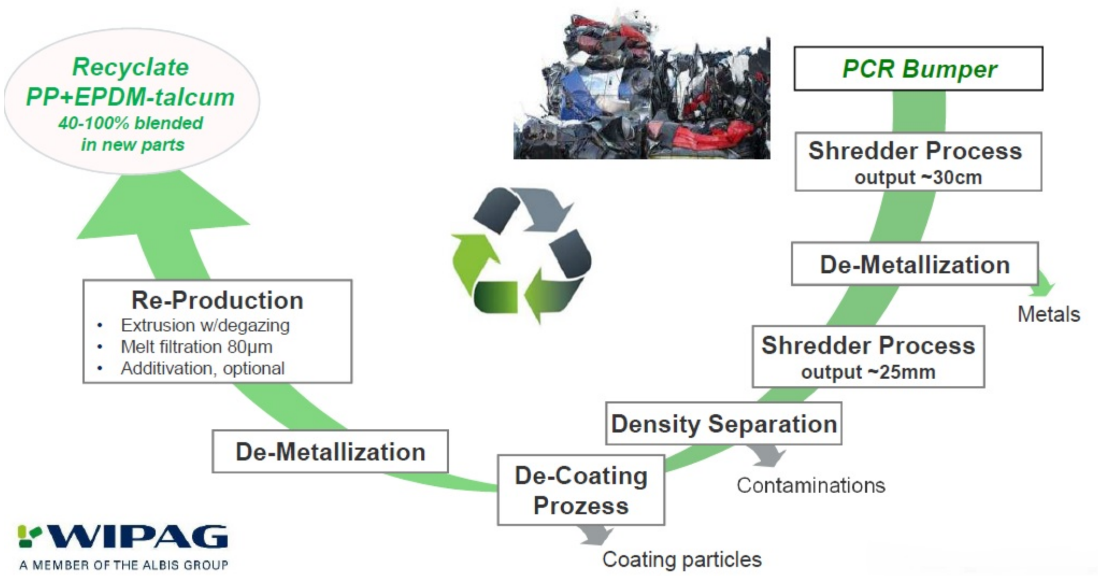

Figure 4.7: ELV bumpers closed-loop recycling process [73]

As mentioned by Gallone & Zeni-Guido, density based separation technique is used by most of the recyclers, but this process generate significant loss of material [36]. The PP compounds with mineral filler (example: talcum) reinforcement content >13%, will lead to density above 1020 kg/m³ [36] and these PP material used in bumpers get separated from the recycling process and considered as waste. According to the study made by Gallone & Zeni-Guido, in an average one quarter of the material from bumper closed-loop recycling is discarded as waste. The estimated average loss of ELV bumper materials during recycling process in year 2030 will be around 9.5%, if no changes in ELV bumper recycling process occurs [36].

The estimated amount of PP materials, out of 172000 tonnes of plastics materials from the front and rear bumpers of 15.1 millions new passenger cars registers in Europe in year 2018, will be around 157000 tonnes (considering a 91% share of PP compounds used for front and rear bumper manufacturing [36]).

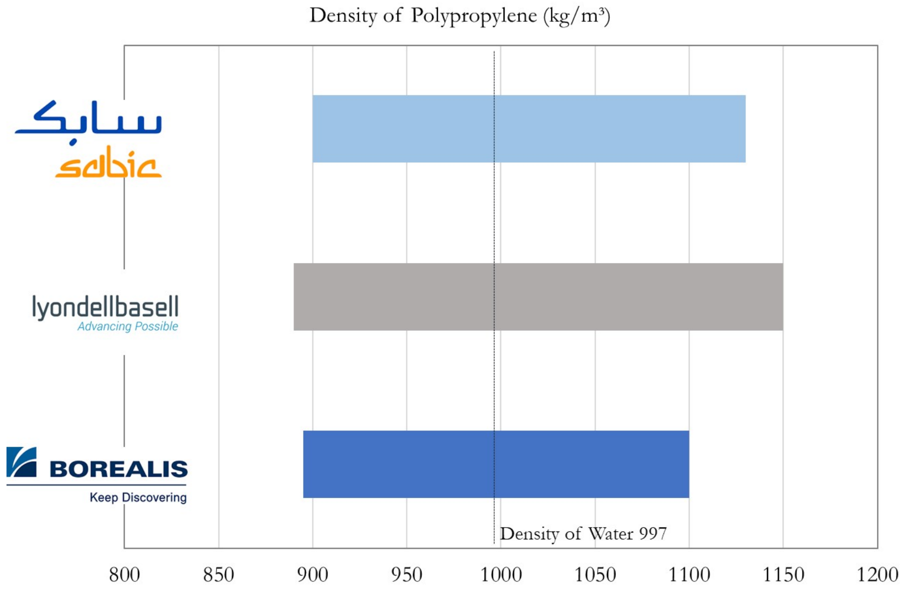

Figure 4.8: Comparison - PP bumper material density (source: [8, 53, 68])

Taking only three of top Polypropylene producers in Europe and their product portfolio for automotive bumper applications into consideration shows that, Borealis offers 23 grades [8], LyondellBasell more than 100 grades [53] and Sabic has around 13 grades [68]. The density range of the PP compounds offered by these three polyolefin producers is shown in Figure 4.8. The figure clearly shows that PP compounds with density ranging between 895 kg/m^3 and 1150 kg/m3 (density of water) is offered for the bumper application by the three material suppliers. From a total 141 grades of PP compounds offered by only three of the material suppliers in Europe, for different OEM bumper applications alone, around 48% of the PP compounds have density higher than floating tank water density (1000 kg/m^3). Assuming that one third of 173000 tonnes of PP material with density >1000 kg/m^3 used for the production of bumpers, which are mounted in European new passenger car in 2018, will cause around 52000 tonnes of PP material loss during the ELV bumpers recycling process in

2029.

The predicted 52000 tonnes of PP material loss is only from bumpers recycling and depending on the parts the material losses vary. According to Klopfleisch, the loss of material during the recycling of dashboards the material loss is very high (60%-70%), due to multi-material design [49]. Considering the share of PP material in automotive application as 26% (as mentioned in Figure 2.4, the ELVs in 2029 is assumed to have approximately 0.8 million tons of PP waste. Suppose one third of the total plastics material from the ELVs is lost due to complications in separation or engineering design or density overlap, the estimated loss would be around 1 million tonnes.

Unless until no changes in OEM plastics material specifications or technological improvements in the material sorting and separation process occur, the huge loss of plastics during ELVs recycling cannot be eliminated. Preventive measures are necessary in plastic material/part specification as well as in design and technology development in the vehicular plastics separation process to eradicate the loss of material during recycling of ELVs and prevent the plastics waste from landfills. Some proposals to reduce the plastics material losses and increase the recycling volume of plastics from ELVs are described in section 4.6.

4.6 Proposals for Increasing Recyclate Market Availability

With the help of literature review, market research data, expert works, interviews and PP bumper case study several proposals to advance the availability of high quality recyclates for automotive applications are identified. The interviewed experts suggested some proposals for increasing the share of recycled plastics in cars, which are mentioned in section 4.4.3. The SWOT analysis results, figure 4.1, show some potential opportunities in the automotive plastic recycling business.

The ELV management, which is one of the most important factors that can highly influence the missing ELVs and thus contribute to the increase in the ELV waste volume. As mentioned in section 2.4, the EU Commissions is leading several steps concerning illegal transport of the ELVs and the missing ELVs in Europe Since ELV management is out off scope of this research work, the ELV topic is excluded. The solutions concerning the plastics material as well as part design and plastics material specifications are of main focus in this thesis and they are detailed in the following sections.

4.6.1 Standardisation of plastics material specification

The bumper case study shows that the usage of different material for a single application by different OEMs can lead to huge material losses during the sorting step of PP bumpers closed-loop recycling process. The main reason for the huge diversified range of PP materials, alone for the bumper application, is the varying material requirements and specifications by the OEMs. In order to meet the bumper material requirements of each and every OEMs, plastic producers develop tailor-made compounds that full the individual OEM specifications. It is impossible to fulfill the performance requirements of all the car manufactures with a single material. The case study focused only on passenger car bumpers, if all plastic parts in the automobile sectors are taken into consideration, the quantity of plastics material loss during ELV recycling would be huge.

One proposal is to standardise the material specifications for each automotive plastic part applications, which should be applicable for all OEMs. For example standardising the bumper material specification of both paintable and non-paintable versions for all OEMs with specified level of talcum content to keep the density low, will increase the efficiency and productivity of the mixed ELV bumpers recycling. Moreover standardisation of plastics material requirements will reduce the diversification of materials available in the market for a single automotive application. As consequence the complexities in material sorting will be reduced, the recovery rate of the ELV plastics waste for recycling can be increased and reduce the cost of the recyclates.

4.6.2 Front loading of design for recycling rules

In order to ease the dismantling, sorting and recycling process of the plastics from the ELVs and moreover to prevent the material losses from the ASR, it is proposed to front load certain design for recycling rules for the plastic materials and their parts by the OEMs to Tiers. Integration of both design for recycling and design for dismantling during material development and parts designing phases, is essential to improve the circularity of the automobile plastic parts. Such design rules should be included by the OEMs in their material specifications and part specifications. And the Tiers are obliged to implement feasible design criteria during the part or material development. Some OEMs have already implemented certain standards or specification from the perspective of vehicle recycling or components dismantling & reusing or using recycled materials.

Since PP material is the highly used polymer for automotive applications, following are some guidelines that could be adopted during designing of automotive PP materials and its components during the development stage, to improve their recyclability after vehicle's end-of-life:

- Mono-material design: Using mono-material design solutions instead of plastic material mix solution for automotive parts, like dashboards, will ease the material separation, sorting and in general automotive parts recycling.
- Density: Especially when using PP compounds for the automotive applications, the density of the compounds should be kept lower than the density of water, so that the material loss can be prevented during the float sink process.
- Color: Carbon black master batches are used to achieve black colored plastic parts for automotive applications. The commonly used material detection method in recycling process is the NIR technology and detection of the black colored parts using this technique is not possible. Usage of non-carbon based color masterbatches or pigments for coloring the compounds is recommended.
- Fillers: Mineral fillers are added in the PP compounds mainly for material cost reduction. If possible unfilled PP should be used for the car parts. In some cases fillers are necessary to improve the performance of parts and in such cases the content of the fillers should kept low, to maintain the density of final compound $<1000\ kg/m^3$.

- Foaming: Using foamed PP can reduce the part weight to a high extend. The design of the foamed parts and the mold are very important to achieve the required mechanical performance of the parts. It is recommended to consider the foamed solution from the beginning of the part design.

- Reinforcement: When using fiber reinforcement, post industrial recycled glass or carbon fibers can be incorporated. Also using fibers from renewable sources like wood are more sustainable.

- Adhesives: For combining two different plastics materials or components, adhesives are commonly used. Avoiding joining of plastics with other materials using adhesives will ease the dismantling. If adhesives are necessary, using environmental friendly, water soluble adhesives is recommended.

- Part Design: During designing the car parts and components the easiness of dismantling the parts should be considered.

4.6.3 Integration of Automotive plastics value chain

An important key in increasing the share of recycled plastics usage in the automotive industry is the full backward integration of the plastics value chain. For attaining the sustainability and introducing more innovative circular economy plastic solutions, the close working between the plastics producers, OEMs, Tiers and plastics recyclers is crucial from the initial stage of new vehicle development projects. The economy and quality of recycled plastics can be achieved also through improving the way plastics and plastics parts are designed and produced.

"Learn from yesterday, live for today, hope for tomorrow. The important thing is not to stop questioning"

Albert Einstein

5
Conclusions

Outcome of this research, answering the initially stated (section 1.2) research questions and objectives, are summarized briefly and concisely in this chapter. The key findings from the market & literature research and the interpretation of the results obtained through empirical research over the closed-loop plastics recycling business in the automotive industry are briefed in the following paragraphs.

The market analysis revealed that the demand for the recycled plastics in the automotive sector is boosting and the share of plastics in the future vehicles is expected to reach 20%. The light weight of plastics help car manufacturers to reduce the vehicle weight and thus reduce the CO_2 emissions or increase the mileage of the E-vehicles. On the other hand the plastics circular economy approach in the automotive industry is of high importance, mainly to ensure the regulatory requirement of the ELV Directive recovery and recycling rate and to reduce the negative impacts of plastics waste on the environment. Moreover the enormous potential of the recycling plastics materials will help the automotive plastic value chain to attain their sustainability targets.

Closed-loop recycling of plastics from end-of-life vehicles as well as post industrial waste can generate the best quality recyclates due to high purity of material and consistency. Moreover these recyclate's performance are high enough that the materials can be re-used for high end automotive application. Despite this advantage recycling plastics from end-of-life vehicles will also reduce the environmental pollution by plastics waste. The scarce availability of recyclates in the market and the price of recycled plastics for engineering application are the main hurdles that restrict their usage in automotive applications

Quantity of high quality plastic recyclates available in the market is the major challenge for the automotive industry to introduce recycled plastics for new automotive parts. Currently only very few small recyclates suppliers are available in the market and their global absence is a drawback, which consequently reduces the partnership potential with big OEMs. Inspite of the increasing share of plastics in the automotive sector, the quantity of post industrial plastics waste or scraps is descending due to advancements in plastics component production and manufacturing technologies and also through introduction of Industry 4.0. The collection and separation of the plastic waste from the ELVs are very complex and cost inefficient due to poor design of the plastic parts.

The usage of different polymer resins for an automotive component lead to complications in separation of the materials and hence cause high material losses during the sorting of automotive shredder residuals. Moreover the complexity of the recycling process allows no cost competitiveness compared to the virgin polymers, which have better performance, consistency and high volume availability. Additionally the high technical material performance requirements by the car manufactures cannot be fulfilled by the recycled plastics, even though the materials are up-scaled by compounding during the recycling process. The material and part specifications for a single automotive application differs from OEM to OEM, leading to wide range of material availability for a single application. The consequence is the loss of material when ELVs from different car manufacturers are recycled together (example

Bumpers recycling). One more important factor is the missing ELVs in the EU, that causes loss of feedstock from recycling within Europe.

The empirical exploration showed that there are several potential solutions to increase the market availability and usage of recycled plastics in automotive applications. Front loading certain rules of design for reusing, recycling and dismantling of plastic parts by the OEMs to the Tiers is a key in developing future automotive plastic parts with life cycle perspective, which will consequently reduce feedstock losses, enable easier sorting, dismantling and recycling at low costs. The standardisation of the material specifications for each plastic application in automobile industry could not only increase the volume of closed-loop recycled plastics rather can also reduce the material development costs and reduce the number of different plastics used in a car. Stricter EU directives with regard to automotive parts or material specifications will enhance the circular economy of the automotive plastics.

One of the main identified obstacles for limited usage of recycled plastics in the automobile sector is the high performance requirements for the recycled plastics by the OEMs. Creation or revaluation of recycled plastics material specification for selected automotive application by OEM, stating only the requirements which are technically feasible, will be highly advantageous for the recyclate suppliers.

Recycling higher volumes of quality plastic feedstocks from ELVs, will reduce the production costs and at the same time increase the material availability in the market. Additionally to reduce the cost of recyclates a cost effective collection of sufficient ELV plastics waste system must be developed by the brand owners and with the support of European Commission's stricter ELV management directive. The European Commission's strong involvement in the ELV management to reduce the illegal transport of end-of-life vehicles outside the EU is very crucial for the improving the circular economy of the automotive and the automotive plastics. Scaling up this closed-loop recycling model and expanding it globally can be achieved only through governmental support of each nations and most importantly new investments in recycling business by the OEMs and material suppliers. For efficient and profitable utilization of the plastics closed-loop recycling, strong integration of the plastics recyclers and ELV recyclers in the automotive plastics value chain is very important.

"Live as if you were to die tomorrow. Learn as if you were to live forever."

Mahatma Gandhi

A

Semi-Structured Interview Questionnaire

Interview - Qualitative Research Method

The structured questions, grouped into four catorgories, which were used during the expert interview are shown in Table A.1.

Interview Questionnaire	
Group 1	Challenges
1	What challenges do you see in usage of recycled plastics for automotive industry?
2	Which feedstock do you consider is the best suitable for the automotive market - domestic wastes or post industrial wastes or post consumer ELV wastes & why?
3	Automotive industry quality requirements are very high; how can plastic recycling technology and industries fulfill all those requirements (material purity, material traceability, material quality consistency, etc.)?
Group 2	Plastic Part Design
4	Car industry uses around 40 different plastics. Considering PP resins different grades - homoPP, coPP, mineral filled PP, fiber reinforced PP, TPOs are available in market. What is your opinion about this multi material usage and what complexities do they have on plastics recycling?
5	Black plastics parts are very common in automotive application. What influences does this have on the recycling process?
Group 3	Proposals for improvement
6	what are your proposals for increasing recycled plastics usage in new vehicles?
7	How are the OEM specifications for the recycled plastics? Do you have any proposals for improvement or changes?
Group 4	Recycled plastics in Automotive
8	Usage of recycled plastics (ex.PP) in AU is gaining more focus. How do you see this market demand and how you see the future for recycled plastics in AU industry?
9	Your opinion about why recycled plastics are considered in Automotive sector?
Group 5	Other Open-ended questions
10	Questions which came-up during the interview session

Table A.1: Semi-structured interview questions

"In this life we cannot do great things. We can only do small things with great love."

Mother Teresa

B

Interviewed Companies

The following tables provide an overview about the interviewed companies details, their products/services, etc.

Borealis AG Company Details	
Company Profile	Borealis is one of the leading providers of Polyolefins, base chemicals and fertilizers. Borealis operates in over 120 countries. Mubadala, through its holding company, owns 64% of the company and remaining 36% belongs to OMV, an international, integrated oil and gas company based in Vienna. Borealis provides services and products to customers around the world in collaboration with Borouge, a joint venture with Abu Dhabi National Oil Company (ADNOC).
Head Office	Vienna
Employees Worldwide	6800
Products	Polyolefins (PP and PE) Base Chemicals Fertilizers
Business Segments	Automotive Energy Pipe and Fittings Consumer Products Healthcare Polymer Solutions Circular Economy Solutions
Production Locations (AU PP Material)	Schwechat- AT Monza- IT Kallo/Beringen - BE Rockport - USA Itatiba - BR
Automotive Products	PP Compounds (unfilled, mineral filled, fiber filled) for interior, exterior and under the bonnet applications Post consumer recycled plastics
Net Sales (2018)	8.3 billion €
Company Website	www.borealisgroup.com
Interviewee	Nicholas Kolesch, Head of Automotive Marketing

Table B.1: Borealis AG [12]

RIALTI S.p.A. Company Details	
Company Profile	Rialti is specialized in manufacturing PP compounds from industrial scrap and post consumer wastes mainly for the automotive market. RIALTI, has more than thirty years of experience in the European polypropylene compounds industry and has established itself as one of the market leaders for PP compounds. Their strengths include high quality technical compounds, both on regenerated or virgin PP bases, employed in several markets like the automotive industry, which has caused the company's rapid growth.
Location	Varesa - IT
Products	Recycled Polypropylene Compounds
Business Segments	Automotive Building Furniture Household appliances and electric devices Others
Automotive Products	Rialbatch - PP mineral filled upto 60% Rialfill - compounds with fibers and fillers filled Rialflame - self-extinguishing PP compounds Rialglass - glass fiber/beads filled compounds E-Rialene - low density compounds Rialtech - tailor-made compounds
Turnover (2018)	37.9 million €
Company Website	www.rialtispa.com
Interviewee	Elena Antonioli, Key Account Manager

Table B.2: RIALTI [66]

WIPAG Company Details	
Company Profile	WIPAG is a plastic recycler with their main focus on the automotive industry. Founded in 1991, WIPAG is a market leader in the development and utilisation of innovative separation technologies. WIPAG recycles the post industrial waste and post consumer wastes like used bumpers from crash-repair and end-of-life vehicles. WIPAG is a member of ALBIS PLASTICS GmbH since 01.01.2018.
Locations	Neuburg an der Donau and Gardelegen - DE
Products/Services	Open Loop Recycling Closed Loop Recycling Recycling-as-a-Service (RaaS)
Business Segments	Automotive
Automotive Products	Recycle PP and PA materials ALTECH IQ WIPAFLEX WIPELAST WIC PP WIC PA
Company Website	www.wipag.com
Interviewee	Tobias Klopfleisch Head of Technical Service & Application Development

Table B.3: WIPAG [83]

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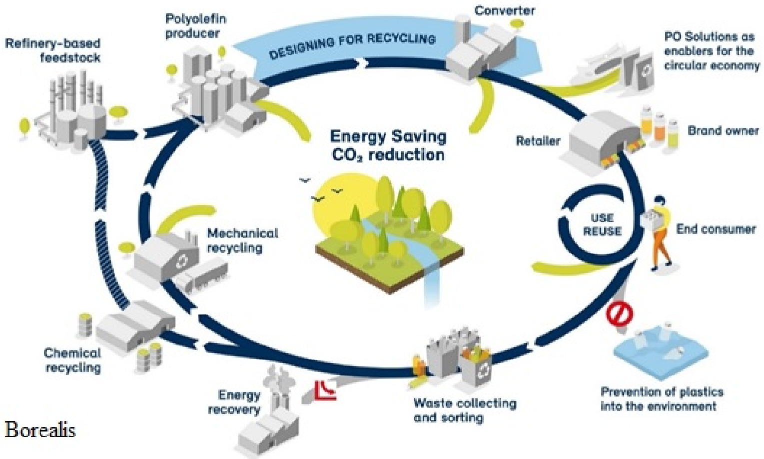

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Circular Economy of plastics will highly contribute to energy saving and reduction of CO_2 emissions. Plastics are a highly valuable, sustainable material, which brings safety, hygiene, comfort and wellbeing to our daily life.

STOP blaming plastics and START proper disposing, reusing and recycling of plastics!
DI Dr. Ramesh Kumar Selvasankar