Defining requirements of PET scrap for open loop recycling of post-industrial waste

by

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Preface

This master thesis was made possible through a collaboration between Diab Group and Miljöbron, I would like to say a special thank you to my two supervisors, Per Hökfelt at Diab Group, and Mats Galbe at the department of Chemical Engineering at the Faculty of Engineering at Lund University.

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Abstract

To reduce the environmental impact and minimize the exploitation of the depleting resources, the transition to a circular economy is vital. It proposes an economy of reduced material consumption and increased reuse and recycling of plastics and other materials. Only last year, 359 million tonnes of plastic were produced worldwide and only a third of the collected waste in Europe was recycled. Among the five largest produced commodity plastics, polyethylene terephthalate (PET) has the highest recycling rates. The recycled PET on the market is mostly post-consumer waste, mainly PET bottles. If bottle-to bottle recycling is to increase, other recycled PET grades need to enter the market. In the production of foamed plastics, waste is produced and accumulated. To decrease the environmental impact of the process it was investigated how to best recycle the waste. The requirements of recycled PET were defined by comparison of existing PET on the market, both virgin and recycled. The most important properties of recycled PET are the intrinsic viscosity and the melting temperature and to be processable they cannot differ considerably compared to virgin PET. Additionally, the quantity and type of contaminants present is important for its recyclability. It was concluded that the plastic scrap from the production has a high intrinsic viscosity and an acceptable melting temperature for reprocessing. However, the plastic waste contains an organic blowing agent and the effect of the compound to reprocessing is unknown and requires further investigation. An economic analysis was made to compare three alternatives of waste handling. It was concluded that the current case with circulation is the most economically beneficial option. Possible applications for the recycled waste was evaluated and several suitable applications were found. The sector with the highest potential was the building and construction sector with applications of high value and good recyclability.

Sammanfattning

För att minska miljöpåverkan och minimera exploateringen av de begränsade tillgångar som finns så krävs en övergång till cirkulär ekonomi. Det innebär minskad materialkonsumtion och mer återanvändning och återvinning av plast och andra material. Förra året producerades i världen 359 millioner ton plast och av det insamlade avfallet i Europa blev endast en tredjedel återvunnet. Bland de fem mest producerade volymplasterna är polyetylentereftalat (PET) den mest återvunna. Den återvunna PET som finns på marknaden är främst från PET-flaskor. För att minska användandet av återvunna PET-flaskor till andra produkter behövs andra typer av återvunnen PET på marknaden, exempelvis från processavfall. Vid tillverkningen av skumplast bildas avfall som sedan ackumuleras. För att minska processens miljöpåverkan undersöktes hur avfallet bäst återvinns. Kraven på återvunnen PET definierades genom att jämföra befintlig PET på marknaden, både återvunnen och jungfrulig. De viktigaste egenskaperna för återvunnen PET är IV-värde (*intrinsic viscosity*), och smälttemperatur och för att kunna bearbetas kan det inte vara betydande skillnader mot jungfrulig PET. Dessutom är mängden och typ av kontamineringar viktiga för att återvunnen PET ska kunna bearbetas igen. Processavfallet från skumplasttillverkningen har ett högt IV-värde och har en acceptabel smälttemperatur. Dock så innehåller avfallet ett organisk blåsmedel och det är okänt hur ämnet påverkar omarbetning och behöver därför utredas ytterligare. En ekonomisk analys gjordes för att jämföra tre alternativ av avfallshantering. Det nuvarande fallet med recirkulering visade sig vara det mest ekonomiska alternativet. Möjliga tillämpningar av avfallet utvärderades och flera lämpliga tillämpningar hittades. Högst potential har byggnadssektorn med flera högvärdestillämpningar med goda möjligheter till återvinning.

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1 Introduction

The resources of our world are being exploited more than is sustainable and scientists all over the world have even declared climate emergency [1]. Despite this knowledge, production and consumption continue to increase. Furthermore, when products have reached the end of their life, they are often thrown away, many times ending up in landfills. The recycling and reuse necessary to reduce the use of virgin raw material are lacking in most production areas. With limited natural resources and the constant threat of climate change, the necessity of circular flows is greater than ever. Circular flows are essential in a circular economy where waste is minimized by recycling and reutilization [2]. This applies to many types of materials, and among those materials, plastics.

Last year 359 million tonnes of plastic were produced worldwide and out of the 29 million tonnes plastic waste collected in Europe, only just over 30% were recycled [3]. Today almost all plastic is produced from fossil sources. The plastics industry in Europe contributes to approximately 130 million tonnes of carbon dioxide to the atmosphere, annually [2]. Besides contributing to the atmosphere with large amounts of carbon dioxide, the fossil sources are quickly depleting and is with the current rate expected to be used up by 2050 [4]. If the life of the produced plastic were to change from linear to circular, less fossil fuels would be required. Furthermore, if the raw material consumption was reduced by increased recycling combined with decreased consumption, the feedstock could in the future consist of only renewable resources. However, the reality is that we are far from reaching solutions to the fossil fuel depletion and climate crisis but creating circular flows can certainly contribute and recycling is a vital part of a circular economy.

There are however multiple difficulties related to recycling and reusing plastics. The quality of the recycled plastic is proving difficult to maintain and therefore many recycled materials are used for production of other products with lower quality requirements. With each cycle of recycling the value of the material decreases and will therefore reach a point where no applications can be found except combustion.

1.1 Project description

Diab is one of the companies making large investments in reducing its environmental impact. The company offers a sandwich construction of a plastic composite with mechanical properties to compete with steel. The plastic composite can be produced from several types of plastics. One of the plastics used is polyethylene terephthalate, commonly known as PET. In the production of PET, plastic scrap is formed during forming and shaping of the product. Most of the scrap is recirculated back in the process but a fraction is accumulated as waste and cannot be used for continued production. However, it is possible that the PET waste can be used for a different application but requires investigation to what application that can be. Furthermore, if another application is possible, the requirements of the PET needs to be specified and be possible to achieve from the production waste.

1.2 Aim

The aim of this study was to investigate the possibility to develop a standardized PET pellet with specified requirements and investigate the market potential of the material. The aim was approached by investigating what uses PET can have industrially and what players are involved. Furthermore, what requirements needed for the PET scraps to be possible for reuse. For instance, purity, thermal and mechanical properties. Whether this standard is feasible to achieve in production and what applications it can be used for was also evaluated.

1.3 Scope

The scope of this master thesis is covering recycling in the perspective of circular economy. It is limited to the recycling of plastics, specifically PET. Furthermore, the discussion is based on other PET products on the market but focuses on the improvements the specific company can make within recycling. The report is not limited to but concentrates on European policies and progress. The perspective is primarily technical and economical with quality as primary focus but identifies other important factors as well. Additionally, no lab work was conducted during this thesis, thus the arguments made is based on facts from found literature.

1.4 Disposition

The report has six sections. Firstly, the introduction with a presentation of the problem statements and the aim of the thesis. Secondly, the background introduces the reader to the area and provides the knowledge needed for the following sections. The third section presents the market and outlooks. Section four clarifies the technical requirements and section five discusses the requirements on the presented problem. Finally, a conclusion is presented in section six.

2 Background

2.1 Polymers

Polymers are long organic molecules, macromolecules, built up by numerous smaller building units, monomers. Monomers react through polymerization to form polymers, either natural or synthesized and a polymer normally comprises of thousands of monomers, connected either linear or crosslinked [5]. The polymerization step usually involves condensation or addition reactions [6]. The formulation and molecular architecture of the polymers can be varied to a large extent, yielding a material with a wide flexibility of properties, choice of feedstock and applications. Important properties of polymers are for instance, molecular weight, glass transition temperature and melting temperature, impact strength and density [7]. Depending on the polymer type, the properties vary significantly. Examples of polymers are plastics, rubbers, fibres, surface coatings and adhesives, all of them materials we take for granted today [6].

A polymer can be crystalline or amorphous. Amorphous polymers have entangled polymer chains and thus, no short-range order. This creates a transparent material that is hard and rigid below its glass transition temperature [8]. The glass transition temperature is the temperature when the amorphous polymer shift from being rubbery or liquid if above, to being hard and rigid, if below [5]. Amorphous polymers with high molar mass above its glass transition temperature show rubbery behaviour, whilst molecules with low molar mass will be liquid above that temperature. If the polymer is heated further, decomposition will occur [8]. On the other hand, crystalline compounds contain 3D-structured, ordered, repeating arrangements yielding different properties than amorphous polymers [6]. Polymers are never fully crystalline, therefore semi-crystalline is a more accurate description. Crystallization occurs when regular structure can be found, hence limiting crystallinity to linear or slightly branched polymers [8].

Because of the diversity and flexibility of the material, the polymers on the market today have a considerable variety of properties. The properties can for instance be physical, thermal, mechanical, chemical, electrical or optical and depending on application the importance of the different properties vary. Properties depend on type of molecule, molar mass, branching, degree of crystallinity, processing conditions etc. High molar mass equals long polymeric chains and certain properties. Intrinsic viscosity is an indicator of molar mass of the polymer and measures the effect on the viscosity from a polymeric solute [6].

2.2 Plastics

The first plastic industries were started in the second half of the 19th century with the production of celluloid and a few decades later followed by Bakelite [5]. Since then the plastic industry have developed enormously and is today one of our most widely used materials. Plastic is as mentioned a type of polymer, and is normally classified in two main categories, thermosets and thermoplastics, according to how it responds to thermal processing [6]. Another common classification is into the categories commodity, engineering and high-performance plastics. Commodity plastics are inexpensively thermoplastics produced in large quantities and for a variety of applications with medium mechanical properties, whilst engineering plastics have high mechanical properties and high-performance plastics are used for high temperature applications [9].

Thermoplastics soften when heated and can therefore be moulded into a desired shape, which hardens when cooled. This type of plastic can be reheated and reshaped many times with little change in properties [10]. Examples of common thermoplastics include low- and high density polyethylene, PE, polypropylene, PP, polystyrene, PS, poly(vinylchloride), PVC, and polyethylene terephthalate, PET [11].

Plastics which are not thermally processable once formed are called thermosets. During curing of polymer resins the individual chains of the polymers are chemically linked by covalent bonds, forming crosslinked networks [11]. The crosslinked network makes the reaction irreversible and the plastics merely decompose chemically instead of softening when heated [7]. Phenol, urea, unsaturated polyesters or epoxies resins are examples of commercial thermosets bases [11].

When choosing material several matters need to be considered. The economic factor is always important together with environmental impact which is increasing in importance. Furthermore, technical considerations such as mechanic and electronic properties are of utmost significance to ensure the product quality. In addition to the former three, appearance is another significant factor [12].

2.2.1 Commodity plastics

2.2.1.1 Polyethylene

With simple structure, low price and ease of processability, it is no wonder that polyethylene, PE, is one of the largest commodity plastics produced today. Example of alluring features include good electrical insulation, good chemical properties, toughness and flexibility. However, it lacks in tensile strength, rigidity and has high gas permeability. PE is a semi-crystalline thermoplastic and are manufactured in different structures, the most common ones being high-density polyethylene, HDPE, low-density polyethylene, LDPE, and linear low-density polyethylene, LLDPE. Examples of applications of LDPE and LLDPE are sacks, carrier bags, film for food wrapping and for the building industry, agriculture. Moreover HDPE are commonly used for pipes, garbage and deep-freeze bags [13].

2.2.1.2 Polypropylene

Another popular thermoplastic is polypropylene, PP. PP has many properties similar to HDPE, including good chemical resistance and electrical insulation properties. Additionally, it contains a steric centre, yielding several possible structures. Isotactic PP has the same configuration of the side chains of the carbon atom along the polymer chain whilst syndiotactic PP has regular alternating configuration. Both types are crystalline and used as engineering plastics, and isotactic PP is additionally used as commodity plastics. The amorphous PP, generally known as atactic PP, with irregular configuration, is commonly used as a binder for plastic materials, for instance in construction. Uses of isotactic PP include injection moulding of complex profiles, fibres, medical products, household appliances and toys. Syndiotactic PP is used for films, injection moulding and in blends with other plastics [14, 15].

2.2.1.3 Poly(vinyl chloride)

One of the earlier polymers to be discovered was poly(vinyl chloride), PVC. PVC is an amorphous thermoplastic and is commonly comprised of numerous additives. Additives used in PVC include stabilizers, plasticizers, extenders, lubricants, fillers etc. The additives make the polymer versatile but also difficult for recycling. Moreover, the sustainability has been questioned due to uses of phthalates as plasticizers, that poses a health risk. In addition, when PVC is incinerated it releases hydrochloric acid which complicates incineration and much of PVC is therefore discarded as landfill. PVC are used widely in building and construction for pipes, profiles, wires and cables and flooring. Furthermore, it is used for single-use medical products and for food films [16].

2.2.1.4 Polystyrene

Polystyrene, PS, is made from styrene and is an amorphous thermoplastic. Characteristics for PS are brittleness and low softening temperature. Expanded polystyrene, EPS, is a foamed structured plastic created using blowing agents, see foamed plastics below. PS and EPS are used for single-use plastics and insulation. Other monomers are combined with styrene to form a more tough plastics, example of other plastics are acrylonitrile butadiene, ABS and high impact polystyrene, HIPS. ABS is an engineering plastic used in the automotive industry and electronic equipment whilst HIPS is used for protective packaging, CD, DVD cases disposable razors etc [17].

2.2.1.5 PET

Polyethylene terephthalate, PET, is the largest commodity polyester and is most commonly used for plastic bottles and fibres and to some extent in engineering applications [11]. Foamed PET are commercially available and lightweight PET foam can be used for packaging whilst rigid PET foam are used in construction and as a core material in sandwich structures [18]. PET is manufactured from dimethyl terephthalic acid, DMT, or terephthalic acid, whereas the latter is more common, and ethylene glycol [19]. PET plastics have good possibilities for recycling and is therefore becoming a more popular choice for plastic products [20].

The crystallized form, CPET can be crystallized up to 60% but crystallizes slowly. However, nucleating agents can be added to increase crystallization rates. Furthermore, crystallinity as well as mechanical properties, e.g. tensile strength, can be increased by stretching. Crystalline pellets are used for bottle manufacturing. Moreover, this creates a biaxial orientation, yielding greater strength in that direction. Other structures of PET are APET, amorphous PET formed when cooled instantaneously and used for fibre production, and PETG, PET modified with 1,4-cyclohexanedimethanol for improved crystallization rates, making it more suitable for injection moulding than unmodified PET. With good mechanical properties and barrier properties after processing, it is suitable for both bottles and fibres. Furthermore, because of its stiffness and its biaxial orientation it is satisfactory for usage in building and construction [12, 19, 21].

The PET quality is most commonly measured in intrinsic viscosity which differs depending on desired application [7]. The intrinsic viscosity is most commonly expressed in the unit dl/g. Examples of intrinsic viscosity required for different applications are presented in Table 1. Several other applications use PET with the same intrinsic viscosity as for bottles as raw material and is therefore commonly referred to as bottle grade PET. Due to the slow crystallization rate, PET is not ideal for injection moulding but the method is used for some applications with nucleating agents added to help crystallization. Instead, extrusion, blow moulding and thermoforming are commonly preferred methods for processing of the polymer [19, 21].

Table 1 The intrinsic viscosity of PET required for different applications [22].

Application	**Intrinsic viscosity [dl/g]**
Recording tape	0.60
Fibres	0.65
Bottles	0.73-0.8
Industrial tyre cord	0.85

2.2.2 Engineering plastics

Materials showing high performance in a combination of chemical, mechanical, thermal and electrical properties are considered engineering plastics. Important polyester thermoplastics include PET and poly butylene terephthalate, PBT, poly(1,3-propylene terephthalate), PPT and poly(ethylene 2,6-naphthalenedicarboxylate), PEN. Examples of other engineering thermoplastics are polyoxymethylene, POM, ABS, styrene-acrylonitrile copolymer, SAN, ultra-high molecular weight polyethylene, UHMW-PE, poly(2,6-dimethyl-1,4-phenylene ether), PPO and polycarbonates, PCs. Engineering plastics can be found everywhere, it is used in packaging, fibres, transportation, medical instruments, audio and video components etc [12]. Moreover, blends of PBT and PET have been used in applications where good surface quality is appealing [21].

2.2.3 Bioplastics

In the search for a more sustainable and environmentally friendly production and material, bioplastics were developed. Bioplastics are divided into two categories, biodegradable and biobased plastics. Biobased plastics are, as the term insinuates, fully or partly produced from biobased resources, i.e. biomass [23]. Several of the conventional plastic types, for instance PET and PE, are being produced from biomass, although the production volumes are substantially lower than the volumes from fossil feedstock [24]. Furthermore, PP and a new polymer, polyethylene furanoate, PEF, are expected to start being produced in a few years. PEF has similar properties to PET and, being completely biobased, is expected to replace PET in packaging applications when established [25]. On the other hand, biodegradable plastics are plastics which can be degraded in the presence of microorganisms. Biodegradable plastics are, however, not necessarily biobased and can be produced solely from fossil feedstock [23]. Examples of biodegradable plastics are starch blends, polylactide, PLA, poly(butylene adipate-co-terephthalate), PBAT, polybutylene succinate, PBS and polyhydroxyalkanoates, PHA. Subsequently, bioplastics is not necessarily more environmentally friendly than conventional plastics and LCA or other evaluations are advocated before assuming bioplastics are completely sustainable [24].

2.2.4 Additives

For specific applications, certain properties of the plastic are required. To acquire the desired properties different types of additives can be used. There are three main categories for additives, the first one is stabilizers or antioxidants to prevent degradation or aging when processed or used. The second category is for controlling the processing of the plastic, for instance, lubricants or blowing agents. Thirdly to improve quality or properties, for example flame retardants, dyes, nucleating agents and plasticizers are added [26]. Furthermore, crosslinkers and chain extenders are chemical agents used to improve interpolymer bonds and chain length to increase properties [18].

2.2.5 Processing

There are many commercial processing methods for polymers for instance, extrusion, moulding, spinning, calendaring and coating [11]. Thermosets are most commonly processed using different methods of moulding whilst in processing of thermoplastics extrusion are most common followed by moulding but calendaring and casting are also frequently used. Moulding processing is discontinuous and shape the plastic using a mould or a matrix. Compression-, transfer- and injection moulding are used for thermosets and injection- and blow moulding and thermoforming are typical for thermoplastics [27].

Extrusion is a continuous operation where polymers are melted in an extruder and thereafter forced into a die for shaping. Using a hopper, the extruder is fed with pellets or powder which then enters the first part of the extruder, the feed. In the feed zone the feed is transported to the next section, the compression zone, by the help of a rotating screw present in the whole extruder. Heaters are placed in the compression zone to initiate melting of the solid pellets or powder. When reaching the last zone in the extruder, the metering zone, the polymer resin has melted completely and is pressed out of the extruder by the force between the rotating screw and the inner wall of the extruder [11].

2.2.6 Foamed plastics

Most polymers can be processed to yield a lightweight material with a wide variety of applications, foamed plastics. Applications include transportation industry and energy industry, which both are industries aiming for reduction of weight without a loss in mechanical properties [28]. Foamed plastics contain two phases, one is the solid polymer and the other is a gaseous phase found in foam cells. The cells are formed during the processing of the plastic and different densities is achieved by varying the volume of the cells [18].

The foamed plastics are categorized in thermosets and thermoplastic foams or in rigid and flexible foams. Rigid foams are crystallized but can also be amorphous if it is below the glass transition temperature of the polymer [28]. The density is an important property of the foamed plastic as well as the mechanical properties. Foamed plastics can, just as other types of plastics, be designed for a wide range of applications. For instance, soft foam is suitable for cushioning and packaging whilst rigid foam is more appropriate for construction applications [18]. It is also advantageous due to its insulating properties such as low thermal conductivity and resistance to moisture [27].

For manufacturing of foamed plastics, the methods foam extrusion, foam injection moulding, and reactive foaming are most common. In foam extrusion a blowing agent is mixed with the melt and when the melt is forced out of the die, this leads to a sudden pressure drop, which initiates the cell growth that gives the foamed plastic its characteristic. Blowing agents are gases injected during the manufacturing process and is what causes the foaming structure with cells containing the gas. There are different types of blowing agents, chemical blowing agents release a gas due to a chemical reaction in contrast to physical blowing agents which change their physical state when heated or pressurized [28]. To some extent inert gases can also be used as blowing agents in, for instance, poly-urethane foaming [29].

2.2.6.1 Sandwich structure

One application for foamed plastics is as the core in sandwich structures. By placing a sheet of foamed plastics between two stiff and thin but strong layers, face-sheets, a rigid material with great strength to weight ratio is formed. Adhesive is added between the face-sheets and the foamed plastics core to merge the materials. Plastic foams utilized in sandwich structures are for instance materials based on PVC, styrene-acrylonitrile copolymer, SAN, polyurethane, PUR and PET. The mentioned foams are used in industries such as marine, wind energy and construction enterprises. For instance, the PET foam produced from Diab is used in wind turbine blade shells [18].

2.3 Recycling

A material has been recycled after being recovered and reprocessed into a product or material [30, 31]. The recycled material can in some cases be used for the same application again but is more commonly processed into another product lower in the value chain. Impurities and lower intrinsic viscosity are two factors that decrease the material value and are essential to reach the desired properties [32]. There are two main types of waste, post-industrial and post-consumer waste. Waste accumulated during processing of the plastic product and never reaches the consumer is post-industrial waste. Material collected from the processing and directly diverted back to the same process as a constituent of the feedstock does is recirculation and does not classify as post-industrial waste [31]. When the product has been used for the intended application and reaches end of life it becomes post-consumer waste. Post-industrial waste is generally cleaner and easier to know the composition of and therefore easier to recycle [33].

2.3.1 Recycling processes

There are several forms of recycling. Primary recycling, a type of mechanical recycling, is when the waste is remoulded or re-extruded directly for the same application, or in another process with similar product requirements. This is only possible with pure material streams and is therefore most commonly applied on post-industrial waste. Primary recycling is also known as closed-loop recycling, which is when recycled material is used for the same application as the original product. The second type of recycling, secondary recycling, is also mechanical and can involve extra purification steps before being reprocessed to products with other characteristics than the original product. Products of secondary recycling is often lower in the value chain owing to lower intrinsic viscosity and impurities. Secondary recycling is an example of open-loop recycling which is when the recycled waste goes into a different application than the original product [32, 34]. Furthermore, a recycled waste used to make a product for the same application as the original product but in a lower ratio have been called semi-closed loop recycling [35].

Mechanical recycling involves grinding, sorting and washing to remove contaminants. For instance, mechanical recycling of PET bottles has been employed for a while and it keeps increasing. Collection and deposit systems are well established, the latter giving cleaner waste streams and hence, seeing better recycling results. The first step of recycling the bottles is grinding, except when PET has been collected with other plastics, then sorting is necessary to ensure pure product streams. After grinding the flakes are washed and separated. Other than PET, the bottles contain PE or PP as lid and paper labels. Due to different densities this is easily separated and labels, glue and dirt are dissolved with caustic soda, resulting in a product with contaminants at ppm level [36]. Mechanical recycling breaks down the chains, decreasing the intrinsic viscosity of the plastic. To counteract this, chain extenders can be added to improve reprocessing possibilities [37].

When the composition of material streams is unknown or involves several polymers, mechanical recycling is difficult. One alternative for impure plastic streams is feedstock recycling, also called tertiary recycling. The plastic is broken down to smaller molecules or monomers with thermal or catalytic processes, for instance pyrolysis, gasification or hydrocracking. Thereafter the chemicals can be used for production of new polymers or fuels [33]. If none of the mentioned recycled methods is applicable, the energy can be recovered by incineration. This is also called quaternary recycling and is strictly speaking not within the definition of recycling since the material is not recovered, merely the energy. However, it is still preferable over landfilling which should be avoided if possible [38].

2.3.2 Circular economy

Numerous solutions to the climate crisis have been suggested, for instance carbon capture and transition to renewable energy [1, 39]. However, to successfully decrease emissions and thereafter continue a sustainable way of living, the production from limited virgin material must be restricted. This is especially true for plastic which is produced from the limited sources of fossil fuels. Besides the obvious solution to reduce material consumption, increasing recycled material as feedstock would minimize the use of virgin material considerably, thereby reducing the environmental impact from plastic production. Moreover, in the future plastic can hopefully be produced solely using renewable feedstock if the virgin material required is minimized as a result of a more circular economy [2].

A circular economy is described as a circular business model where reducing consumption, reusing, remanufacturing and recycling materials are the priority to decrease the need for virgin material, thus reducing the environmental impact. Circular economy is vital for a sustainable future and is perfectly achievable [40]. However, actions towards a circular economy must be taken now, rather than later. The recycling of materials is essential for a functioning circular economy and the obstacles that recycling of plastics face, must be overcome. One of the difficulties with recycling and reusing waste is lack of applications or rather lack of known applications. For many industries, the waste produced cannot be used in the same process again, thus needing a new application. The new application is often a downgrading, but it is essential to lessen the downgrading as much as possible, hence maximizing the number of cycles the material can be recycled. Furthermore, a considerable lack of standards of recyclable plastic obstruct the search of applications for the plastic waste. A circular economy is not only sustainable, it is also economically beneficial [2, 4]. Given that an application is found for the waste, it can be sold and thereby become an income rather than a cost. The principle of a circular economy is illustrated in Figure 1. The idea is to maintain a circular flow with recirculation in every step, thus only requiring a small quantity of virgin feedstock.

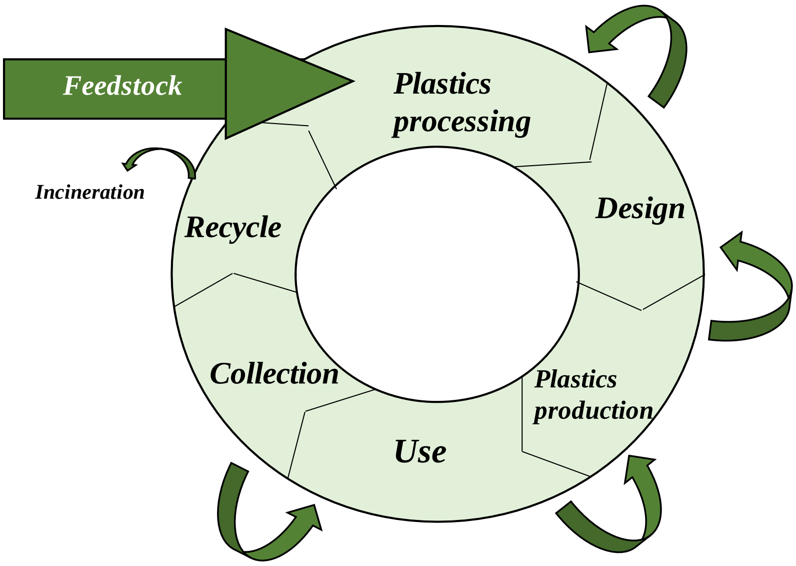

Figure 1 The Circular Economy of Plastics. The waste produced in each step is recovered and the products are recycled at end of life to minimize the quantity of virgin material needed.

2.4 Processing of PET at Diab

The foamed PET plastic manufactured at Diab is processed by extrusion. The processing of the foamed PET is continuous and is made from virgin PET bottle grade pellets. To achieve the desired mechanical properties, several additives are mixed with the polymers. The additives needed in this process are a physical blowing agent, chain extender and crosslinker and a nucleating agent. The blowing agent is a liquid organic compound with low boiling point, added to achieve the foamed structure. The chain extender and crosslinker is added for elongation of the polymer chains and for creation of bonds between the polymer chains.

The PET pellets are stored in silos. The pellets are firstly transported to dryers to remove all moisture. Thereafter the pellets are mixed with the agglomerated waste, nucleating agent, cross linkers and chain extenders in the first extruder. When the constituents are melted and mixed, the blowing agent is added. The hot melt is then cooled and heated repeatedly in the second extruder to achieve an even temperature profile throughout the melt. When the melt reaches the end of the second extruder it is pushed out of a die out on a conveyor belt, where it is instantly foamed because of the blowing agent. The foaming creates a big rectangular like shape with uneven edges and corners.

After leaving the extruder the now foamed polymer requires cooling, shaping and rotating to ensure the desired properties. The plastic is cooled on a conveyer belt with the surrounding air as coolant. It is thereafter cut into smaller pieces to prepare for rotation. Before rotation, the uneven edges need to be cut clean. Thereafter the pieces are rotated 90° to achieve the right direction of the high mechanical properties. When rotated, the plastic pieces are welded together. In the next step they are cut once again, into the correct dimensions for the boards. A flow sheet of the process can be seen in Figure 2.

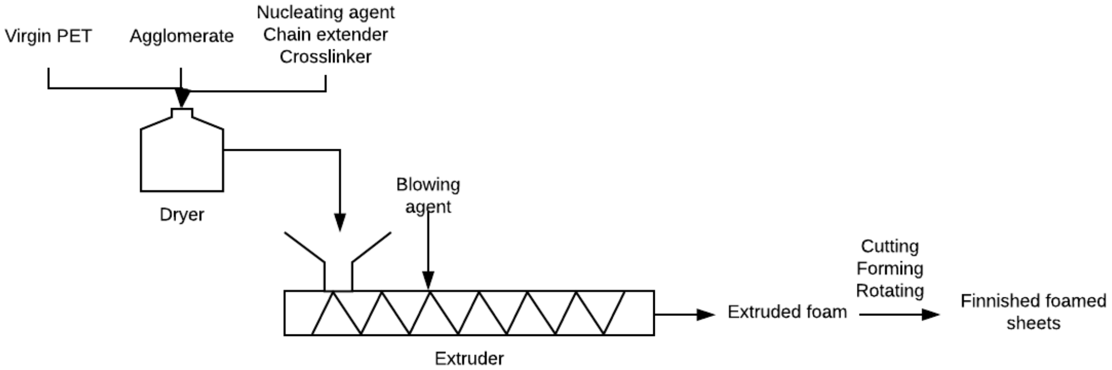

Figure 2 The process of foamed PET production. The raw material is mixed and dried before entering the extruder and adding the blowing agent. The extruded foam is shaped accordingly to achieve a foamed sheet of desired dimensions.

The dust formed during cutting and forming of the boards are collected and transported to an agglomerator. The agglomerator presses the dust together, to form an agglomerate. The agglomerate are uneven, irregular flakes, the size is varying between 2-7 mm by length and 2-3 mm by width, see Figure 3. The agglomerate has similar properties and composition to the main product, but with a lower intrinsic viscosity due to chain degradation. Because of the uses of chain extenders, the intrinsic viscosity is between 0.9-1.0 g/dl, a higher intrinsic viscosity than the virgin material. Furthermore, the density of the agglomerate is similar to the product, 1200 kg/m^3 but has lower bulk density, approximately 500-550 kg/m^3 compared to 750-800 kg/m^3 of the product, due to its irregular shape. Consequently, the agglomerate consists of mostly PET plastics, with small amounts of blowing agents, chain extender and cross linker. These properties combined with a high intrinsic viscosity yields a high-quality post-industrial waste.

Figure 3 Picture of the agglomerated PET.

3 Plastics and recycling market

3.1 Distribution of plastics

3.1.1 Distribution

The plastics production has increased enormously since the start in the 19th century and keep increasing with a production of 359 million tonnes in 2018, excluding the production of synthetic fibres which add another 67 million tonnes [3, 41]. As explained above, plastics include a wide variety of types and forms shaped specifically for numerous different applications. The biggest application for plastics is packaging, followed by building and construction. Plastics can be found in most sectors, the full distribution can be seen in Figure 4 [3].

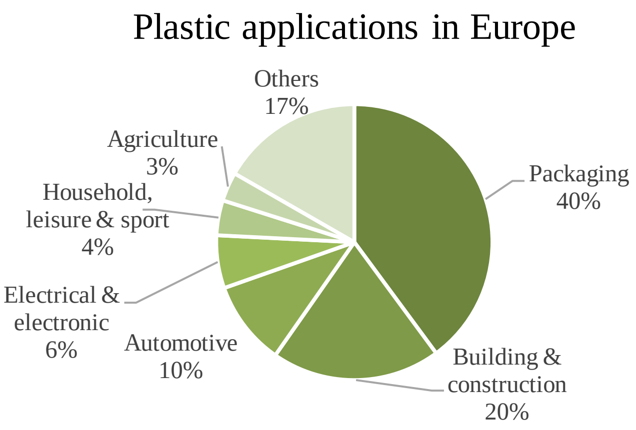

Figure 4 The distribution of plastics in Europe within the applications packaging, building and construction, automotive, electrical and electronic, household, leisure and sport, agriculture and others.

Among the different plastic types, PE is most common, produced both with low and high density depending on application. The second most abundant plastic is PP followed by the other big commodity plastics PVC, PUR, PET and PS. However, even though only a few types of plastics are produced in massive bulks, other types of plastics cover 19% of the market, as seen in Figure 5 [3]. This shows the big diversity with plastics and how many different types are available. Furthermore, the plastics of the same types does not necessarily contain the same additives making the variety even greater. Moreover, it also highlights one of many problems with recycling namely to acquire the high requirements of pure product streams for easier reuse and reprocessing. With countless types of plastics, the collection and separation are proven difficult.

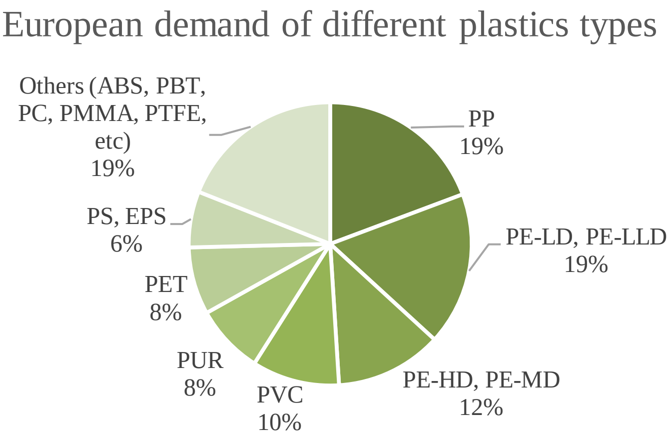

Figure 5 The demand of different plastics types in Europe. The figure shows PP, PE, PVS, PUR, PET, PS and others.

The popularity of the different plastics varies greatly depending on what sector and application it is and what properties are required. In packaging the most common plastics are PE, PP PET and to some extent also PS. In contrast, the building and construction industry prefers plastics with high mechanical or insulation properties. For instance, PVC, HDPE and MDPE, EPS and PUR. Moreover, engineering plastics are growing in popularity as a substitution of metals with its lighter weight and possibility to tailor its properties [21].

3.1.2 Plastics production

Even though there is a consensus about the necessity to decrease material production, the plastics production has kept increasing and the last couple of years the increase was more than ten million tonnes per year. The production in Europe is no exception to the increase, until last year when production decreased with a few million tonnes. The estimated values are presented in Table 2 [3, 42, 43].

Table 2 The global and European production of plastics in 2016, 2017 and 2018.

Year	Global plastics production (tonnes) [3, 42, 43]	European plastics production (tonnes)
2016	335 million	60 million
2017	348 million	64.4 million
2018	359 million	61.8 million

More than half of the global plastic production is in Asia, with 30% placed in China. The rest of the world shares the second half of the plastic production with North American Free Trade Agreement, NAFTA, and Europe in the top. The full distribution is presented in Figure 6.

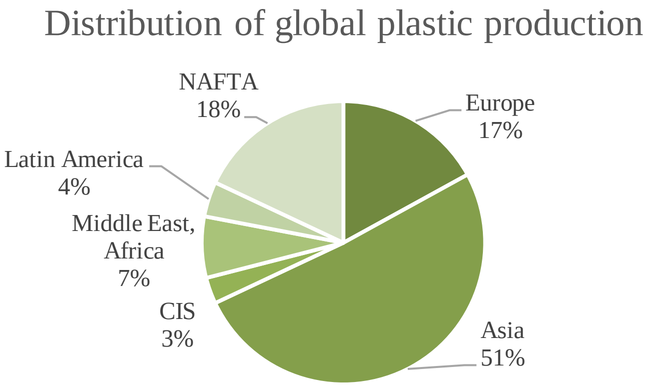

Figure 6 The distribution of global plastic production between Europe, Asia, CIS (Commonwealth of Independent States), Middle East and Africa, Latin America and NAFTA (North American Free Trade Agreement).

3.1.3 Bioplastics

Out of the millions of tonnes of produced plastic in 2016, only two came from biobased resources. This equals less than 1% of the global plastics production, with the rest coming from fossil fuels. The biodegradable plastics represent approximately 43% of the produced bioplastics with starch blends and PLA being the main types. PBAT, PBS and PHA are also common biodegradables. The other 57% is biobased, non-degradable plastics where PET is the dominant type with 27% of the bioplastics market. Other common types include polyamide, PA, polytrimethylene terephthalate, PTT, and PE. Production of biobased PP and PEF is expected to start in 2023, and is believed to have big potential, PP in several applications and PEF in packaging specifically [25, 43].

3.1.4 Polyester market

In 2016 the global production of polyester was almost 77 million tonnes, making it the most commonly used polymer. Most of the produced polyester is used for fibre production, mainly synthetic fibres in the form of filament and staples are the dominant application of polyesters. This represents 44% and 20% of the polyester market, respectively. Besides fibres, a big part of the polyester production is for PET resin for a variety of applications and a smaller part to produce film and other polymer resins [44].

The main application for PET resin is bottle production, where carbonated soft drink is the main application but bottles for water and other drinks are also produced in large quantities. Other food applications include packaging and films and only 6% of the PET production is for non-food applications [45]. Examples of non-food applications are cam wheels, gear teeth and bearings, industrial tire cords, fuel pump and fuel system components. PET is also used for switches, relays, connectors, wiring devices etc. for electrical applications. Furthermore, PET blends with different additives are widely used for engineering applications. PBT have more engineering applications than PET, mainly due to its faster crystallization rate which makes it easier to process [12, 21, 46].

3.2 Recycling market

3.2.1 General recycling

The recycling of post-industrial waste is difficult to measure since the waste is mostly handled by the industries themselves in contrast to post-consumer waste where collection, sorting and separation is performed by separate companies. Even though exact data on post-industrial waste is difficult to obtain, it is known that post-industrial recycling rates are high, considerably higher than post-consumer waste [47]. Post-industrial waste is less contaminated and often mono streams, hence it is easier to recycle than the mixed plastic waste streams coming from post-consumer waste.

In contrast to post-industrial recycling, post-consumer waste recycling is monitored yearly. The recycling rates in Europe are generally low but are improving. Last year the recycling rate was 32% out of the 29 million tonnes collected post-consumer plastic waste. The recycling is almost solely mechanical recycling; only Germany and Italy utilize feedstock recycling and only in small fractions. The majority of the waste is going to energy recovery, 43%, and the rest is landfilled. The landfilled waste is decreasing every year, but still reached 25% in 2018 [3]. However, the numbers are calculated from the amount of waste collected, and not from discarded waste. Therefore, it is probable that the recycling rate is considerably lower than the 32% mentioned above. Furthermore, a trend worth mentioning is that recycling and energy recovery is generally higher in countries with landfill bans for instance, Sweden and Switzerland [3]. Previously, much of the plastic waste have been exported to China for waste handling but have now stopped due to a ban on Chinese import of plastic waste, implemented in 2017. Subsequently, this ban now forces countries to find other solutions of waste handling [48].

Concerning the different sectors, packaging has the best recycling rates whilst agriculture, automotive, electronics and building and construction are considerably behind. The agricultural sector has high potential with clear material streams. However, the material is contaminated with soil which is difficult to separate in an economical feasible way [49]. Electrical and electronic applications are often difficult to separate, hence are more suitable for feedstock recycling or energy recovery. Construction and automotive recycling rates are increasing. Furthermore, both are long term applications and much of the produced material is still in use.

Closed loop recycling is generally easier than open loop recycling to establish since the desired application and requirements of the recycled material is clear. On the other hand, open-loop recycling is more flexible about quality since the application can vary. Consequently, an application for the recycled material needs to be chosen first. Thereafter the requirements and processing can be decided, thus open looped recycling requires more work to sort out logistics and administrative matters. Clear standardizations of different recycled plastic materials would simplify open loop recycling, thus hopefully increase recycling and circularity rates.

Out of the material that is recycled, only a small fraction is closed looped. Most recycled materials are downgraded into products with lower value, and often directly to low value products, thereby preventing more than one circle of the material [50]. Furthermore, the price of recycled plastics varies depending on quality and demand, but is on average 50-60% of the price of virgin plastics [51]. If materials were recycled to products with highest possible value instead, the material could be recycled multiple times and thereby maximizing the value and create a more circular flow. Low value applications for recycled materials include plastic pipes, plastic lumber and waste collection bags. Even PET, which has high recycling rates, do not often have closed-loop recycling, instead the majority of the recycled PET are for other lower value applications. For instance, 80% of recycled PET are turned into polyester fibres for textiles and carpets [50].

With increased interest of recycling, in addition to post-consumer collection of waste, multiple recycling platforms have been initiated. The platforms are made for companies to easier find possible buyers or products to buy. Examples include Scrapo for international users, and Recycla, established for Swedish companies [52, 53].

3.2.2 PET recycling

Collection and recycling of PET have been monitored closely in multiple countries during the past decade. Especially recycled PET bottles are measured and have a well-developed market. However, the recycling rates vary enormously depending on country, the figures for 2017 and 2018 are presented in Table 3. United States has the lowest recycling rates of the countries mentioned with a rate of only 29%. In contrast, Japan has a considerably higher rate with over 80%, similar to Swedish recycling rates. Several other countries in Europe have high recycling rates, for instance Finland and Germany. However, the average value is brought down by southern European countries, resulting in an average of 58% [54-57]. Given the high consumption volumes in the US and Europe, an increase in recycling rates would contribute with substantially more recycled material on the market.

Table 3 Numbers of PET bottles sold and recycled and recycling rates for the countries United States, Japan, Sweden as well as Europe.

Country	Bottles sold (kt)	Bottles recycled (kt)	Recycling rate (%)
United States (2017) [54]	2700	780	29
Japan (2017) [55]	590	500	85
Europe (2017) [57]	3300	1900	58
Sweden (2018) [56]	27	22	83

Applications of recycled PET bottles are aiming towards bottle-to-bottle, meaning closed-loop recycling of drinking bottles but recycled PET are also used for sheets, fibres, and strapping. In 2017 the distribution in Europe was 40% for sheets, 29% bottle-to-bottle, 15% fibres and 15% for strapping and others [57]. PET can be used for numerous products. Sheet applications include trays for food, industrial products, partitions for food, blister packs and business supplies etc. Examples of uses of fibres are materials for cars, bedclothes and other home interior details, clothes, housekeeping items; drainer bags and dust cloths, materials for engineering and construction such as insulation and various other products such as tents, nets and work gloves. PET can also be used for moulding applications, bags, stationaries and bottles for non-food applications. Furthermore, PET can also be used as an additive, a constituent of paint or films etc [55].

Most recycled PET found on the market are from PET bottles. The market has had time to develop and grow. With environmental topics being high on the agenda, the demand for recycled materials has also grown and thereby increasing demand of recycled PET bottles [36]. This has resulted in a volatile market with varying price and lack of recycled material. The price is dependent on oil price and of demand, and price for recycled PET has at times been as high as the price for the virgin material. This is especially true for food grade recycled PET, because of the higher requirements for the material [58]. Moreover, the demand of constant supply of recycled material is a necessity for production companies and difficult for the recycled bottle market to meet. Furthermore, with increased quality of recycled PET bottles, the bottle-to-bottle recycling rate is expected to increase, leaving the other actors looking for recycled PET with barely anything.

3.3 Outlook

3.3.1 Future of plastics

Although plastics production in Europe decreased in 2018 compared to the year before, the worldwide production of plastics increased and is expected to keep expanding, even if not in Europe [3]. Because of the flexible properties of plastics and wide variety of its applications it is difficult to find substitutions for all applications. However, there are ongoing research about alternatives, and production of biobased and biodegradable plastics is expected to increase in the coming years. The quantities will be far from replacing all fossil-based plastics the biobased and biodegradable plastics but will definitely help to contribute to a more sustainable industry [25]. Furthermore, the conversion from a linear to circular economy is essential to avoid depletion of natural resources and to achieve a sustainable future [50].

3.3.2 Future of recycling

Recycling rates for plastics are increasing in Europe and have done so the last couple of years [3, 42, 43]. This positive change is proof that the industry is moving towards a sustainable future. However, the recycling rates need to improve substantially before the environmental goals are reached. Furthermore, regarding PET bottles the bottle-to-bottle recycling is increasing as well as the demand of recycled PET [54, 55, 57]. Because of the increasing demand of PET, more recycled PET needs to enter the market, thus great potential in the field exists for actors looking to sell PET waste. Other plastic types are being recycled but to a lesser extent and with lower secondary applications. Furthermore, landfilling need to stop completely and incineration of plastics need to be reduced [32]. Factors helping and obstructing the change towards a circular economy are discussed below.

3.3.3 Incentives

The largest incentive for the use of recycled materials for plastic converters are increased profits [59]. Recycled materials are often cheaper, hence the raw material cost is decreased for the company. Furthermore, companies with plastic waste will also benefit economically by selling waste for the use as recycled materials instead of incineration or landfilling.

The environmental impact of the plastics industry cannot be denied, and it is therefore essential to adapt the industry to a sustainable trade. Increasing the use of recycled materials is a crucial step, leading up to a circular economy with minimal waste. When a circular economy is achieved only a fraction of virgin material will be needed and this can hopefully be produced from solely biobased resources, making the plastics industry sustainable and independent from fossil fuels. For plastic converters, one incentive for increase in recycling and the use of recycled material is to become more environmentally friendly. Furthermore, the image as environmentally friendly from costumers is another attractive feature for companies [59].

Policies can help to force incentives, for instance landfill bans are applied in the Nordic countries and the countries show high recycling and incineration rates [60]. In general, the European countries with landfill restrictions show higher recycling rates than countries without it [3]. The European Union has during the previous decade implemented numerous directives for sustainable production, use and waste management and more forced incentives are expected to come and is necessary to accomplish the transition to a circular economy [61, 62].

3.3.4 Barriers

The development of the recycling market is moving forward, but slowly. Several insecurities on the market are hindering the development. Plastic converters in Europe state that discontinuous supply and the varying quality of the recycled material are two major barriers for using recycled materials [59, 63]. It is a known problem with post-consumer waste that both quality and reliable supply is difficult to achieve. However, with more post-industrial waste on the market, a higher quality and a more continuous supply could be achieved since companies often yields mono-streams or waste streams with known composition and have a regular production. However, this requires more transparency regarding the composition of post-industrial waste. Because of secrecy with material composition and other company specifics, it is unlikely that the market suddenly will be overfilled with high quality waste. Nevertheless, clearer standards and markets would simplify for other actors than waste handlers to increase sale of recycled materials. Furthermore, standards for performance or quality of products would increase certainty and standards for clearer definitions of recycling terms, which would help to open up the market [59, 60, 64, 65]. Moreover, creating standards for products to minimize amount of colorants and other additives to reduce contamination of the plastic waste streams enable an easier recycling process with a purer secondary material as outcome [47]. This design from recycling principle is about designing products with the aim for it to be recycled. An example is the upcycling of post-industrial PP waste done at a university in Belgium. The recycled PP was matched to a specific product in regard to its properties to ensure an application with as high value as possible [66].

Price volatility has also been a concern. The price of recycled material is dependent on both virgin prices which vary, but also on current demand [47]. Furthermore, shortage of PET bottles can be seen due to the social movement towards sustainability and the accessibility of recycled PET bottles makes it the supposedly preferred raw material. Thus, the demand increases and contributes to increased prices of PET bottles [65]. The use of recycled materials in food-contact applications are problematic and are hindered by legislations. However, bottle-to-bottle recycling is an example of the uses of recycled material within the sector even if the raw material choice for food applications are more restricted than other sectors [36, 59].

Policies implemented by the EU have been mentioned; however, in several areas policies are lacking clarity or completely missing. For instance, policies about reuse, repair and remanufacturing, the responsibilities of second hand products on the market from producers and buyers respectively and for efficient and functioning waste markets. Furthermore, policies are needed not only from EU but also from national and regional authorities as well as from companies. Cooperation from all involved actors will be necessary to reach environmental goals put up [61, 67].

The mentioned factors contribute to the insecurities which in turn decreases the demand of recycled plastics. For a functioning market, a constant demand is crucial and it is currently lacking considerably [68, 69]. The incentives mentioned previously and the proposed solutions to the existing barriers will hopefully contribute to a larger recycling market with clearer boundaries in the near future.

4 Defining requirements of recycled PET pellets

4.1 Existing PET grades

4.1.1 Virgin PET

There are numerous different PET grades on the market, depending on application. Virgin PET can be bought with an intrinsic viscosity ranging from approximately 0.6-0.86, glass reinforced up to around 30%, with flame retardants and other additives depending on what properties are desired. Furthermore, both amorphous and crystalline grades as well as modified PETG can be found [70]. However, bottle grade PET is the most popular grade and is most frequently used for drinking bottles, but is also used for other applications, for example in the production of foamed plastics at Diab. Bottle grade PET has an intrinsic viscosity between 0.73-0.8 and is therefore of sufficient quality for multiple applications [22].

4.1.2 Recycled PET

The recycled PET on the market today is mainly from post-consumer waste because of its easy accessibility. The amount of post-industrial PET on the recycling market is difficult to find because it can only be found in company records, but rates indicate that much post-industrial waste is recycled [47]. Because of the difficulties to measure quantities of post-industrial waste on the market, data of recycled PET from bottles will be used for the discussions to follow. Recycled PET contains more contaminants than virgin PET and the composition is not always known. This decrease in quality is problematic for manufacturing as well as dilemmas of legislations and regulations of waste [71]. This is especially true for post-consumer recycled plastics that besides additives from production can contain traces of polyolefins such as PE and PP, PVC or other plastic types [72]. PET has the advantage of being an inert material, thus it does not absorb much of other compounds and therefore is easier recycled [36].

4.1.2.1 Bottle grade PET

PET bottles are widely recycled and is the most common type of recycled PET found on the market. Far from all recycled bottles are being recycled to bottles but the numbers are increasing, hence leaving a lesser quantity of recycled bottles for other applications [57]. Consequently, this contributes to an uncertainty with supply that companies cannot afford. Moreover, the uncertainty with price is an additional complication. On the other hand, the advantages of recycling PET bottles are many, the biggest one being the wide collection and recollection systems implemented worldwide, ensuring quantities of recycled waste. Furthermore, the lack of additives and ease of separation from the PP or PE lids and paper labels gives a recycled material with only small amounts of contaminants [36].

However, when collected with other plastic waste, separation becomes more difficult and the recycled material can contain more contaminants. Because of the wide uses of PET as material in food applications high requirements of the material is required. Moreover, the presence of non-food containers in PET bottle waste streams complicates the recycling process. If non-food bottle containers increase in the collection rates, better purification steps will be required to use the recycled material for food applications [36]. The intrinsic viscosity tends to be lower with recycled PET due to the degradation of chains during mechanical reprocessing but can be counteracted with chain extenders; hence, no significant decrease in mechanical and thermal properties can be seen [73-76].

Properties of virgin PET resin and recycled PET bottles can be seen in Table 4. The main difference in composition between virgin PET and recycled PET bottles is the contaminants present after recycling. Nevertheless, the intrinsic viscosity of recycled PET bottles is similar to virgin PET resin. Furthermore, the thermal properties of the recycled PET do not alter significantly to the virgin, and nor does the Young's modulus. However, a considerably decrease in elongation at break can be seen in the recycled material.

Table 4 Properties of virgin and recycled PET. Physical properties, thermal properties, mechanical properties and the quantity of contaminants are presented.

Property	**Virgin PET resin**	**Recycled PET bottle flakes**
Intrinsic viscosity (dl/g)	0.76-0.85 [73, 77]	0.77 [73]
Density (kg/m^3)	1300-1400 [12]	960 [78]
Bulk density (kg/m^3)	800 [79]	290-480 [80]
Thermal properties		
Glass transition (°C)	80 [73, 76]	81 [73, 76]
Melting point (°C)	247 [73]	249 [73]
Mechanical properties		
Young's modulus (MPa)	767 [74]	709 [74]
Elongation at break (%)	270 [73]	5.4 [73]
Contaminants		
PVC (ppm)	-	20-6000 [72, 73]
Other plastics (ppm)	-	0-7000 [72]
Trace metals (µg/l)	-	0-80 [74]
Labels (ppm)	-	10 [80]
Colours (ppm)	-	100-1000 [80]
Moisture (%)	0.3 [77]	<0.6 [80]

The main consequence of the contaminants is discolouration, much instigated by coloured PET flakes but also from other contaminants [22]. Contamination of other plastic types obscures reprocessing, for instance traces of PS, PP, PE and other plastics [81]. Furthermore, the presence of PVC contributes to degradation of the polymer chains by production of hydrochloric acid when degrading, reducing the intrinsic viscosity of the recycled PET considerably [82].

4.2 Requirements

For plastic converters to use recycled plastics, the recycled material must fulfil the same requirements as the virgin material to achieve satisfactory quality and quantity of the product. This requires a recycled material with high purity and high technical properties as well as continuous production of recyclable waste to ensure a steady supply and sufficient quantity of feedstock.

4.2.1 Supply

For industries, the quantity of post-industrial recyclable plastic to be delivered continuously could be the percentage waste produced from each production cycle. For instance, on one of its production sites, 26% of what Diab will produce is waste, although it is recirculated in the process. Furthermore, when errors occur, waste accumulates quickly. Consequently, more recyclable material is produced. However, the second type of waste is more difficult to predict and is not continuous and therefore more challenging to sell off. Due to this, industries with continuous production of recyclable waste is the main focus and the irregular quantities of waste will be included when applicable.

4.2.2 Quality

The technical aspects are crucial for a recyclable product. If the recycled plastics do not meet the requirements, there is risk of failure during processing. The processing through injection blow moulding, extrusion or thermoforming are most common for PET and the recycled plastic needs to meet the requirements for each method. Although the recycled resins have similar properties as virgin PET, processed samples often demonstrate a considerable decrease in properties [72]. It is the quantity and type of contaminants that determine the processability. It is therefore essential to know the highest level acceptable for each type of contaminant before processing. Most research have been executed with post-consumer waste because of its higher quantities of contaminants and a selection of requirements of important properties for reprocessing of post-consumer recycled waste are presented in Table 5.

Table 5 The properties required of recycled PET for it to be recyclable.

Property	Processable recycled PET [72]
Tm (°C)	>240
Intrinsic viscosity (dl/g)	>0.7
Moisture (wt%)	<0.5
Size of flakes (mm)	4<D<8
Metal content (ppm)	< 3
PVC content (ppm)	< 50 ppm
Polyolefin content (ppm)	< 10 ppm
Dyes content (ppm)	< 10

The conclusions from the study discussed earlier [72], are that the most important properties to remain constant are melting temperature, for equal processing temperature, and the intrinsic viscosity. Intrinsic viscosity is used as the main characterization of the quality of PET [7]. Furthermore, metal content and other types of plastics need to be minimized.

The research of the effects of the contaminants in post-industrial waste is not as extensive and public. However, the contaminants are often fewer and the exact composition of the waste is known which is a considerable advantage. Even if the exact composition is not published, the company can do a proper evaluation of the eventual effect of contaminants in recyclable waste. Furthermore, the most problematic compounds are other types of plastics, metals and dyes which post-industrial waste and the PET waste discussed in this report most often does not contain. Nevertheless, considerations to other contaminants present need to be taken.

4.3 Proposal of properties for standards

To clarify the technical quality of recycled PET, a proposal of important properties to include to potential buyers of recyclable waste is presented. Considering the properties mentioned above, the most important properties are the melting temperature and intrinsic viscosity. Additionally, consideration to the type of contaminants present in the waste need to be taken. To simplify standardization, a comparison of relative properties is proposed.

A proposal of what the maximum decrease in properties of the secondary material should be to be processable are presented in Table 6 as well as the resulting acceptable recyclable PET. The relative properties presented is the percentual difference between virgin PET and recycled PET possible for processing to see how much the recycled PET can be degraded and still reprocessed according to literature. The numbers are calculated from how much the properties of processable recycled PET from Table 5 differ from the properties of virgin PET from Table 4, relatively, see Equation 1.

Table 6 Proposed required melting temperature and intrinsic viscosity for PET to be recyclable and percentage difference in processable PET and virgin PET.

Property	**Percentage difference in processable secondary material vs virgin material (%)**	**Acceptable recyclable PET**
Melting temperature	-2.8	247±7 °C
Intrinsic viscosity	-7.9	0.76±0.06 dl/g

$$\% = -\frac{P_{virgin\ PET} - P_{processable\ rPET}}{P_{virgin\ PET}} \quad (1)$$

The melting temperature can only differ a few degrees in the recycled PET from the virgin PET for reprocessing in similar processing conditions as with virgin PET. The intrinsic viscosity shows a higher accepted percentual difference, where the limiting factor will be lower intrinsic viscosity since higher intrinsic viscosity constitutes no problem. Following this, PET waste within the accepted intervals should be possible to reprocess and use as recycled material. Additionally, mechanical properties need to be taken into consideration as well, to make sure the recycled material withstands the requirements.

The degree of downgrading in the secondary material calculated here is best applied for similar applications as the original product, in other words closed loop recycling or semi-closed loop recycling. A lower intrinsic viscosity can still be sufficient for low value applications. In contrast, the melting temperature is less flexible as it is the decisive parameter for the processing temperature needed. The properties required will depend largely on application, high quality applications, for instance engineering plastics will have higher requirements than low quality applications, such as fibres or strapping [12].

It is difficult to set a level for the quantity of contaminants present in the PET to be recyclable because of the wide variety of contaminants possible and the difference in impact it causes. The importance should therefore focus on the properties that are easier to measure, i.e. intrinsic viscosity and melting temperature and to evaluate the effect of the contaminants individually with respect to the secondary material and the envisaged application. Additionally, the size of the flakes, pellets, agglomerate or whatever shape the secondary material has will matter. If the size of the particles of the recyclable waste is too big or too small, reprocessing will be difficult and complicated and consequently, more costly. The size of the recycled material should therefore be monitored and to be possible to reprocess, ideally similar size to the virgin pellets.

4.4 Discussion

To use recycled PET for closed loop recycling or other high-quality applications the plastic waste is required to maintain the properties as the raw material; thus, it must not show significant changes in intrinsic viscosity, melting temperature and mechanical properties. In semi-closed loop recycling, the recycled plastic is recycled into products with similar qualities as the original product, but in a lower ratio. Consequently, this is fitting for recycled PET with medium to high quality, i.e. PET waste with a slight decrease in properties or containing contaminants [35]. When the quality of the recycled PET is not sufficiently high for closed loop recycling, open loop recycling is applied instead.

Furthermore, open loop recycling can be used when the waste shows a decrease in properties compared to the virgin material, or because of legislations or other reasons cannot be used within the same application again. However, if possible, recycling is still advantageous and can be used for plastic applications with a variety of qualities. Finding the appropriate treatment option corresponding to the quality of the present waste has been found to increase the circular economy performance of the process [35].

The biggest obstacle for using plastic waste as feedstock is generally the quality, mainly the contaminants. Post-industrial waste can offer a higher quality of plastic waste with fewer types and quantities of contaminants. However, additional factors are important for a supplier to invest in recycled material. For instance, continuous supply and the shape and size of the waste. Therefore, to sell waste as a recycled material a constant production of waste is necessary. Furthermore, the waste needs to come in a shape and size possible for processing, for instance in shape of pellets or flakes. Regarding quality it is important to know the properties and the effect of the present contaminants to ensure a delivery of a waste with said properties. For instance, to have the said intrinsic viscosity and to fulfil the said mechanical strength. Moreover, a continuous and steady level of the quality instils confidence of the manufacturer. Depending on quality of the waste it can go to high-, medium- or low-quality applications. The different applications are discussed further in the next section.

For increased recycling, the long-term solution is to change the design of the products and its processes to produce products using additives in smaller quantities and that are more sustainable and easier separable. Moreover, a reduction of the number of different additives used can help for standardization. Standards for recycling are difficult to achieve for several reasons. There are numerous types of additives with varying degree of loss in properties if present in reprocessing. Furthermore, the multiple applications on the market for PET, all with different requirements for the material is another factor. This makes waste plastics extremely difficult to standardize into one type. Just to decide what properties to define by is troublesome because depending on application, different properties are the most important. However, in general intrinsic viscosity is the dominant measurement of PET quality. Melting temperature is also important because of processing conditions. Additionally, secrecy from companies makes it harder to know what additives are used and the effect it has on reprocessing.

To help standardization, a presentation of relative properties was proposed by comparison of literature data and can be used to estimate if the PET waste is recyclable. However, more comparisons are needed to statistically confirm the feasibility as well as reprocessing with the proposed method to prove its validity. When plastic converters use recycled PET, it is often as a mix with virgin PET. It is likely a fraction of the raw material always has to be virgin to ensure sufficient quality but with more recycled PET of higher quality this fraction can be minimized, and the majority of the raw material is recycled waste.

5 Implementation of recycling PET scraps

5.1 The agglomerate

5.1.1 Properties

The agglomerate from the production is post-industrial waste by definition [31], and the composition of the said waste stream is known to be similar to the product. Subsequently, the agglomerate contains mostly PET with small amounts of blowing agent, chain extender and nucleating agent. It does not contain any other plastic type. Moreover, when the PET is cut, the cell structure is partly broken and the blowing agent can therefore diffuse, and thus the dust used for the agglomerate contains slightly less of the blowing agent. The chain extenders constitute no obstacle for reprocessing, on the contrary the chain extenders help to keep the intrinsic viscosity sufficiently high [37]. Furthermore, the nucleating agent present is a very small dose to initiate the foaming, or in other processes to increase crystallization and should therefore not affect the quality of the material. The organic blowing agent is as many other organic compounds flammable, which could affect reprocessing and could constitute a bigger problem to reprocessing. However, the agglomerate is recirculated into the production of foamed plastics within the process, hence constituting no additional problem to the process. Furthermore, the limit of recirculate is limited by the lower intrinsic viscosity and not by the quantity of the blowing agent. On the other hand, it is not known how the blowing agent affects reprocessing for other applications not involving the blowing agent as input material. The properties of the agglomerate are presented in Table 7. The exact composition of the agglomerate is not presented due to secrecy, thus an approximate is presented instead.

Table 7 The properties of the agglomerate. Physical properties, thermal properties, mechanical properties and the quantity of contaminants are presented.

Property	**PY agglomerate**
Intrinsic viscosity (dl/g)	0.9
Density (kg/m^3)	1200
Bulk density (kg/m^3)	500-550
Size (mm)	2-7*2-3
Thermal properties	
Glass transition (°C)	75
Melting point (°C)	250
Contaminants (wt%)	<10%
Blowing agent (wt%)	<5%
Chain extender (wt%)	$<m_{\text{Blowing agent}}$
Nucleating agent (wt%)	$<m_{\text{Chain extender}}$

The intrinsic viscosity and melting temperature are comparable with virgin PET shown in Table 4. The intrinsic viscosity is even slightly higher due to the present chain extenders. Besides the contaminants, the properties of the agglomerate are comparable to the properties of virgin PET. However, the mechanical properties of the agglomerate have not been measured and can be the limiting factor if they show a considerable decrease compared to the virgin PET. It is therefore essential to measure the mechanical properties, i.e. tensile strength, elongation at break, Young's modulus, to conclude the quality of the waste. Furthermore, the moisture content of the agglomerate is another property important to know, because of the difficulties with reprocessing if too much water is present [72].

The blowing agent has a low boiling point, thus being volatile and probably escapes the recycled material when processed at the required temperature. Furthermore, other foamed plastic types, for instance expanded polystyrene, have been reported to lose its foaming properties when recycled [83]. This insinuates lower quantities of the blowing agent in the recycled agglomerate.

5.1.2 Quality

Because of the high intrinsic viscosity and similar melting temperature as virgin PET, the quality of the agglomerate is considered high. The percentual difference in melting temperature is small, and the intrinsic viscosity is considerably higher than the virgin PET, see Table 8. Equation 1 was used for the calculations. Comparing the percentage difference to Table 6, the melting temperature is within the range of accepted temperature for processing conditions used for virgin PET. Furthermore, the intrinsic viscosity is higher than the presented percentage.

However, a higher intrinsic viscosity does not constitute a disadvantage. On the contrary, the higher intrinsic viscosity the more complex application it can be used for.

Table 8 The percentual difference in melting temperature and intrinsic viscosity between the agglomerate and virgin PET.

Property	Agglomerate percentage difference
Melting temperature	+1.2
Intrinsic viscosity	+18.4

The agglomerate has the advantage compared to post-consumer waste of containing few contaminants, thus simplifying recycling. However, the organic blowing agent as one of the contaminants is an uncertainty, which may pose challenges. To know the hazards of the blowing agent, safety data sheets can be used. The safety data sheet can give an understanding of the risks involved with the specific chemical. Additionally, an investigation in what the effects of the blowing agent are more specifically is required for a better understanding. Furthermore, for better knowledge of the processability of the agglomerate the mechanical properties and moisture should be measured as well.

5.1.3 Supply

For a plastics manufacturer, continuous supply of raw material is essential. Thus, a continuous production of plastics waste suitable for recycling is required to establish a relation with a regular purchaser of the waste. In the current factories owned by Diab, one of them continuously produce more waste than can be recirculated. The factory produces approximately 2 tonnes of plastic waste per week. With a production of 50 weeks per year the factory produced 100 tonnes of plastic waste per year.

Additionally, several new factories for foamed PET production are planned or have just been initiated. The process itself is designed to minimize waste produced, thus not producing waste on a continuous basis, if working properly. However, when faults occur, waste is accumulated quickly. For instance, one of the planned production facilities will produce 1.2 tonnes/h and if there is an error for 2 hours, 2.4 tonnes of plastics waste are produced. Furthermore, when the production is stopped, the extruder takes a couple of hours to start again. During this time, extruded PET without the blowing agent is produced in big lumps and collected. Consequently, during only a few hours of complications, many tonnes of plastics waste is produced. The big disadvantage of this type of waste is that the big lumps of plastics is not processable without grinding or other methods to dissemble the material into smaller parts. Moreover, it is difficult to guarantee a continuous supply of the lumps, because of its dependency on complications in the production. However, when the production facility has been active and ran continuously for a certain amount of time and with an average of production stops, the quantity of waste produced can be calculated. The waste produced in irregular intervals, the plastics lumps, will be purer than the agglomerate because of the absence of the blowing agent, thus containing more PET and it can be easier to reassure buyers of the quality. However, because of the shape of the waste it is difficult to handle but can be an asset if resolved how to grind it. Additionally, the two different types of waste need to be labelled separately to know what waste contains the blowing agent.

5.1.4 Standards

The plastics agglomerate produced from Diab will always have similar composition because of the same input material. Slight differences in content of the contaminants can occur when the waste is agglomerated because of a difference in composition of the dust compressed. However, the differences will be small, and the plastic waste will be of consistent quality. This simplifies recycling since the company can be confident that the properties required are delivered to the buyer according to a set standard. The standard should include intrinsic viscosity, melting temperature, mechanical properties and if possible, the quantity of contaminants or the very least the effect the contaminants can have on reprocessing.

5.1.5 Incentives

The incentives for individual companies in terms of recycling are big. Both financial and environmental benefits are achieved as well as the waste handling is solved efficiently. By selling off waste the process becomes more profitable. An establishment on the recycling market for a company could be, besides good marketing, a way to find new customers as well as new opportunities within sustainability, i.e. new raw material or new applications for the agglomerate. Furthermore, an increase in reuse and recycling can lead to fulfilling requirements to be established as a green investment and a better image for the company [84].

5.1.6 Barriers

The big technical issue with the agglomerate is the contaminants, especially the blowing agent and the uncertainty of the consequences of reprocessing. This issue is enhanced by the nondescriptive quantity of the blowing agent that comes with process secrets. This barrier can be partially resolved by research of how the contaminants affect PET when used in other applications to ensure potential customers of its quality. A long term solution is to design the product with the recycling process in consideration, for example by changing the blowing agent to an inert gas, e.g. carbon dioxide which has been successfully tried by others and reduced the hazards of the contaminants [29]. Furthermore, the undefined market and lack of standards hinders the establishment of the secondary market and contributes to uncertainty when the agglomerate is put on the market. Additionally, the undefined market reduces the demand, creating a more difficult climate to find customers.

Legislations to take into considerations are mainly about waste handling but also the legislations concerning the different applications. For instance, food grade applications have high requirements on raw material, production and product, which the agglomerate does not fulfil.

5.2 Possible applications

5.2.1 Type of recycling

The wide variety of properties achieved from plastics in general, and PET in particular, gives numerous options of possible applications for the plastics waste produced. The ideal option would be closed loop recycling to a product with similar properties as the original product, thus yielding no considerable downgrading on the value of the product. However, the agglomerate cannot be used in the production of foamed PET at Diab in a quantity of more than 30% of the feed, and it is therefore unlikely that another producer of foamed PET can use solely the agglomerate as feedstock.

When closed loop recycling is ruled out, the next option is semi-closed loop recycling. In this case the agglomerate is used in combination with virgin PET as feedstock. Much like the current process Diab uses, with the difference that the latter is defined as recirculation rather than recycling. In contrast, if another company would use the plastic waste produced it would classify as recycled waste. This option is theoretically possible but would then include selling the waste to competitors. If this is plausible it would mean minimum downgrading and give a high value to the recycled material and opening the possibilities of several cycles of the recycled material in the value chain. However, finding and establishing a collaboration might encounter other obstacles such as process secrets.

The third and most probable option is open loop recycling, with a variety of options of application with varying value. Open loop recycling often involves considerable downgrading. The ideal solution would therefore be an application with as high value as possible, to maximize the number of cycles possible for recycling. An additional step is to consider recycling of the plastic waste the product will become after its life cycle. Even though the application for the foamed PET has a long lifetime the question of how to handle the waste is relevant. Therefore, the different recycling options should be considered and evaluated for appropriate waste handling when the time comes.

5.2.2 Business sectors

Plastics is used in most sectors and there are therefore many options of recycling. The sectors to be discussed are packaging, electrical and electronics, automotive, agriculture, household and leisure, building and construction and others.

PET is well established in the packaging sector and include drinking bottles, containers and films. However, most are in food contact applications, where the requirements are strict. Because of the strict requirements, the quantity of recycled food grade PET on the market is low but have a high demand, thus there is a lot of potential if an agglomerate suitable for food applications could be achieved. Currently, this is not the case, and any food grade applications can therefore be ruled out. An example of this is a company producing plastics for retail applications being interested in the agglomerate. Upon further conversations it was discovered that all of the PET products possible was within the requirements of food contact applications and the discussions came to an end. After excluding food packaging as an option, non-food packaging remains. Non-food packaging is the smaller application within packaging for PET but is still seen in bottles for cleaners etc. Subsequently the options are few, hence not the ideal sector. The next sector, agriculture will just as the packaging sector be sensitive to hazardous compounds considering contact with food and animals. However, smaller plastic applications and fibre applications exist in the sector.

Another option is electrical appliances and electronics where PET can be used for parts in switches, relays etc. Since plastic is used frequently as an insulation material in electronics, the recycled agglomerate could have a future there. However, the material needs to be stable enough for electronics and it must be fireproof, and with the contaminants present in the agglomerate it cannot be guaranteed without testing. Furthermore, this sector will only use PET as a small constituent in blends with other materials, making the new product difficult for recycling. Recyclability of the new product is important to take into consideration when choosing the appropriate application and the electronic sector is therefore not ideal when opting for a circular economy.

In the building sector multiple applications are possible. Firstly, foamed plastic applications with lower requirements of the raw material than the original product could be an alternative. Foamed plastic applications would have the advantage of similar composition as agglomerate and low decrease in value. Another possibility is glass fibre reinforced recycled plastics, that have been noted to perform equally well as virgin reinforced plastics [85]. Reinforced polyesters could be an alternative in building and construction applications [46]. With the contaminants present in the agglomerate, applications less sensitive to the presence of organic compounds are preferable, making the building and construction industry a good option. Furthermore, since the original product is used in the building and construction sector, staying in the same sector simplifies legislations and regulations. Engineering plastics made of PET are used within the sector and is a good option. Cam wheels and gear teeth are other possible options for the agglomerate. Additionally, lower value applications are possible in the sector with the agglomerate, examples include filler in concrete or other materials [86, 87]. However, filler applications have low value and is difficult to add another recycling cycle to and it should therefore be seen as a last option before energy incineration. In conclusion, the building and construction sector has multiple possible applications with varying value and ease of recycling and it should be investigated further.

One of the major applications of PET and recycled PET is the fibre industry, much of it ending up in the household and leisure sector as clothes, carpets, etc. Recycled PET used for textiles are in high demand and instead of using recycled PET bottles, the agglomerate could be used as a raw material. However, fibres do not have as high requirements of intrinsic viscosity, thus a value loss will occur if this application is chosen.

The automotive sector is generally not a big sector for PET, but polyester fibres is used for the interior in cars and for tire cords. Moreover, the automotive sector is as several other industries looking to decrease its weight and the quantity of material required, requirements which foamed plastics or other plastics can help to achieve. The sector could therefore be a potential user of recycled plastics if exchanging more of the material towards plastics.

Because of the wide uses of plastics, there are multiple other applications not fitting into a particular sector. For instance, road bumps, strapping, medical applications. The former two are low value applications that different plastic types can be used for. Medical applications are not suitable with high quantity of contaminants because of the environment it is aimed for. Furthermore, PET can be used in mixes with other plastic types, as additives and as other small constituents in a wide variety of uses and it is therefore difficult to locate all applications possible. In addition to the applications mentioned for PET, an alternative can be to substitute other plastics or other types of material, i.e. metal or glass, for PET.

5.2.3 Application value and recyclability

When choosing application for the recycled PET it is important to consider upcoming recycling cycles as well, hence choosing an application with high enough value for easily continued recycling. High value applications include engineering plastics, which often has high intrinsic viscosity, thus the advantage of the high intrinsic viscosity of the agglomerate can be used. Applications with PET as the main material and with an intrinsic viscosity close to the agglomerate minimizes the decrease in value of the secondary product and gives good possibilities for another recycling cycle. Even an application with intrinsic viscosity around 0.75 dl/g, similar to bottle grade, gives a low decrease in properties and can be considered of high value.

The next option is medium value applications with a decrease in intrinsic viscosity and consequently, other properties. Medium value applications can still have high purity of PET, for instance fibres or films. The fibre industry is huge with a high demand of polyester and still has high possibilities of recycling because of high quantities of relatively pure PET. Even though the value is decreased, the material still has enough value left for recycling a second time.

When no other applications for the recycled materials can be found, low value applications can be an alternative. The lower valued applications are a considerably decrease in value from the original product and will be difficult to recycle due to its low quality. Furthermore, low value applications are often mixtures of different plastics or containing only a small constituent of PET in combination with another material. Subsequently, in this case recycling is difficult or costly and is therefore at the end of its life cycle instead incinerated or landfilled. For example, road bumps, plastics in concrete etc.

For the second product to be recyclable it has to be mostly PET or is easy to separate from the other materials. Consequently, most blends are not recycled, at least not to products of high value. Concerning this, if possible an application with only PET or with only small quantities of additives should be chosen, instead of mixed plastics blends or applications with PET as filler.

5.2.4 Discussion

Because of the high requirements of the original product, the agglomerate is not suitable for closed loop recycling. Thus, the recycling type best applicable on the agglomerate is open loop recycling. Furthermore, several business sectors have potential for using the recycled agglomerate. For instance, building and construction and electrical and electronics as good areas for high value applications with several engineering applications. Additionally, lower value applications are found in household and leisure and automotive industry, with fibres as the main application. Other applications are mainly low value applications and should together with filler applications be avoided if other options are possible. The most value-added application possible should be applied to minimize value decrease and thus maximize the number of recycling cycles possible. In contrast, packaging and agriculture have low potential with few suitable applications. For the chosen application to have good recyclability in addition to high value, building and construction is to prefer over electrical and electronics. This is because of the difficult separation of materials in electrical and electronics which leads to its low recycling rates. On the other hand, applications in building and construction has generally a longer lifetime as well as increasing recycling rates.

Depending on what application the agglomerate is used for, a variation in selling price is to be expected. Higher value applications are more likely to return more profit for a higher quality whilst low value applications with lower requirements will probably only pay as much as the value of other raw material used. However, as mentioned previously, it is unlikely to get more than 60% of the value of virgin PET for the agglomerate. The geographical location is another factor to be considered. Preferably, the location of the factory for the chosen application is close to where the agglomerate is produced to minimize transport costs and emissions. Furthermore, because of the several production sites worldwide that is or will be producing the agglomerate, the application can vary depending on what exists nearby. Additionally, nearby is relative and can vary to everything between from the same city to the same continent.

5.3 Economic analysis

To evaluate the economic benefits of selling of the agglomerate for recycling, three cases were investigated. The current case with recirculating the agglomerate, a second case with selling the agglomerate instead of recirculating and a third case to incinerate the waste instead of using the agglomerator. The cases will be evaluated on cost, income and turnover per hour. The term turnover used will not be the overall profit of the company but rather an estimate in income after the material cost is subtracted from the calculated income from sold product to gain a comparative value. An additional comparison on turnover per year with the same definition will be made to evaluate the difference. Additionally, to verify the result achieved, a full economic analysis is required.

5.3.1 Cases

The following calculations are based on estimates of cost for the virgin material, and income of sold product and agglomerate. The sold product is estimated to have a value five times greater than the virgin material costs. Moreover, the recycled agglomerate is estimated to have a value of 50% of virgin material costs, taken from the average value of recycled plastics compared to virgin plastics [51]. The assumptions for the calculations are based on a factory, that has an extruder with an input rate of 1200 kg/h. The process achieves a yield of 80%, the remaining 20% are transported to the agglomerator and thereafter recirculated into the process. The production hours are calculated on a production of 300 days/year with a 24 h/day production without stops. The values used in the calculations are presented in Table 9. The calculations are only based on material costs and does not cover other production costs or other company expenses. The calculations should therefore not be seen as a representation of the total turnover of the company, merely a comparison between the three cases to estimate which yields the highest turnover.

Table 9 Production rates and price parameters used in the calculations.

Rate	**(kg/h)**
Extrusion rate, m_E	1200
Product, m_P	960
Agglomerate, m_A	240
Price	**(€/kg)**
Virgin material, P_V	3
Product, P_P	15
Transport to waste handling, P_{transp}	0.1
Incineration, P_{incin}	0.05
Landfill	0.1
Production of agglomerate, P_{PoA}	0.4
Agglomerate sold, P_A	1.5

5.3.1.1 Case I

The first presented case is the current method used with recirculation of the agglomerate. The extruder is fed with 80% virgin PET and 20% of the recirculated agglomerate. The finished product is sold, and the waste is transported to the agglomerator and thereafter recirculated into the process. The material costs for case I will be the cost of the virgin material, and the cost of producing the agglomerate, se Equation 2. The income will be the product volume times the value of the product, presented in Equation 3. This leads to the calculation of the turnover in consideration to income and material costs, and yearly turnover, in Equation 4 and 5.

$$Cost_{Case\ I} = m_P \cdot P_V + m_A \cdot P_{PoA} = \frac{960kg}{h} \cdot \frac{3€}{kg} + \frac{240kg}{h} \cdot \frac{0.4€}{kg} = \frac{2\ 976€}{h} \tag{2}$$

$$Income_{Case\ I} = m_P \cdot P_P = \frac{960kg}{h} \cdot \frac{15€}{kg} = \frac{14\ 400€}{h} \tag{3}$$

$$Turnover_{Case\ I} = Income_{Case\ I} - Cost_{Case\ I} = \frac{14\ 400€}{h} - \frac{2\ 976€}{h} = \frac{11\ 424€}{h} \tag{4}$$

$$Yearly\ turnover_{Case\ I} = Turnover_{Case\ I} \cdot t = \frac{11\ 424€}{h} \cdot \frac{7\ 200h}{year} = \frac{82.3M€}{year} \tag{5}$$

5.3.1.2 Case II

In case II the option of selling of the agglomerate instead of using it is evaluated. Consequently, the material costs will be higher due to production of agglomerate and additional virgin material to make up for the sold off agglomerate, see Equation 6. The income in case II will be the sold product and the sold agglomerate, Equation 7. Equation 8 shows the turnover for case II. An additional calculation for case II was made, to prove that the price of the sold agglomerate must be the same as the virgin material price to gain the same turnover as in case I, presented in Equation 9. Equation 10 calculates the yearly turnover.

$$Cost_{Case\ II} = m_E \cdot P_V + m_A \cdot P_{PoA} = \frac{1\ 200kg}{h} \cdot \frac{3€}{kg} + \frac{240kg}{h} \cdot \frac{0.4€}{kg} = \frac{3\ 696€}{h} \tag{6}$$

$$Income_{Case\ II} = m_P \cdot P_P + m_A \cdot P_A = \frac{960kg}{h} \cdot \frac{15€}{kg} + \frac{240kg}{h} \cdot \frac{1.5€}{kg} = \frac{14\ 760€}{h} \tag{7}$$

$$Turnover_{Case\ II} = Income_{Case\ II} - Cost_{Case\ II} = \frac{14\ 760€}{h} - \frac{3\ 696€}{h} = \frac{11\ 064€}{h} \tag{8}$$

$$P_{A-new} = \frac{Turnover_{Case\ I} + Cost_{Case\ II} - m_P \cdot P_P}{m_A} = \frac{\frac{11\ 424€}{h} + \frac{3\ 696€}{h} - \frac{960kg}{h} \cdot \frac{15€}{kg}}{\frac{240kg}{h}} = P_V = 3€/kg \tag{9}$$

$$Yearly\ turnover_{Case\ II} = Turnover_{Case\ II} \cdot t = \frac{11\ 064€}{h} \cdot \frac{7\ 200h}{year} = \frac{79.7M€}{year} \tag{10}$$

5.3.1.3 Case III

To compare the cases of recirculation (case I), and sale of agglomerate (case II), a third case was evaluated. In case III there is no production of agglomerate, instead the dust produced is transported to waste handling, in this case incineration. The transport and the incineration add an extra cost to the production, the calculation is shown in Equation 11. The income is the sold product, see Equation 12. Finally calculating the turnover and yearly turnover respectively, in Equation 13 and 14.

$$Cost_{Case\ III} = m_E \cdot P_V + m_A \cdot \left(P_{transp.} + P_{incin.}\right) = \frac{1200kg}{h} \cdot \frac{3€}{kg} + \frac{240kg}{h} \cdot \left(\frac{0.1€}{h} + \frac{0.05€}{h}\right) = \frac{3\ 636€}{h} \tag{11}$$

$$Income_{Case\ III} = m_P \cdot P_P = \frac{960kg}{h} \cdot \frac{15€}{kg} = \frac{14\ 400€}{h} \tag{12}$$

$$Turnover_{Case\ III} = Income_{Case\ III} - Cost_{Case\ III} = \frac{14\ 400€}{h} - \frac{3\ 636€}{h} = \frac{10\ 764€}{h} \tag{13}$$

$$Yearly\ turnover_{Case\ III} = Turnover_{Case\ III} \cdot t = \frac{10\ 764€}{h} \cdot \frac{7\ 200h}{year} = \frac{77.5M€}{year} \tag{14}$$

5.3.2 Comparison and discussion

The calculated values from each case is presented in Table 10. The three cases presented all have a profit but differ in how much.

Table 9 The calculated material cost, income, turnover, yearly turnover and difference in turnover for Case I, II and III respectively. The turnover is defined as the difference in income and material cost and takes no other costs into consideration.

Case	**Material cost (€/h)**	**Income (€/h)**	**Turnover (€/h)**	**Yearly turnover (M€/year)**	**Difference in turnover**
Case I	2 980	14 400	11 400	82.3	-
Case II	3 700	14 800	11 100	79.7	-3.2%
Case III	3 640	14 400	10 800	77.5	-6.2%

The yearly turnover presented is huge. However, this does not cover any costs except the cost of the raw materials; therefore, it should not be seen as a representation of the total turnover of the company. Consequently, the high number is not relevant, instead the difference in turnover between the cases is the interesting result. Furthermore, a percentual difference has been calculated to highlight the interest in the difference between the cases rather than quantity.

Not surprisingly, the best turnover is achieved from case I. Case I has the lowest material cost because of its usage of recycled material. Case II has higher income than the other cases since another product, the agglomerate, is sold in addition to the product. However, the material costs are higher because a larger use of virgin material, as well as the production cost of the sold agglomerate. The lower income of selling the agglomerate as recycled material does not make up for the higher material costs and consequently, the turnover yielded is lower than in case I. For case II to be as profitable as case I, the calculations show that the agglomerate needs to be sold at the same price as what the virgin material costs. Considering that the average value of recycled material is considerably lower than for virgin material, it is unlikely the agglomerate will be purchased for the same price as virgin PET, unless there is lack of virgin material or very high demand of recycled PET. With a purer agglomerate containing less to no additives the value could increase and come closer to the value of virgin PET. Even a switch to a less hazardous blowing agent could increase the value of the agglomerate. It is however unlikely even then that the agglomerate can be sold for more than virgin PET, thus making case I the more profitable option.

The case of incineration, case III, yields the lowest turnover. This is because even though the cost of producing the agglomerate is eliminated, an additional cost of waste handling is added instead. The plastics transported to the waste-to-energy plants will be dust with a very low density which complicates transport. Additionally, when using the plastics for energy generation, a value is achieved. However, there is a higher value of reusing the plastics for other applications, and is therefore more advantageous than incineration, especially considering the transition towards a circular economy. Incineration has a place in the circular economy, but it should be seen as the last option after all possibilities of recycling has been ruled out.

Both case I and II are beneficial in a circular economy perspective with the reuse of the plastics waste. After comparing three alternatives for the produced plastics, it can be concluded that during the current circumstances case I, the presently used option, is the most profitable.

5.4 Discussion

The agglomerate is a recycled PET waste comparable to virgin PET concerning melting temperature and intrinsic viscosity. The high intrinsic viscosity yields good prerequisites for high value applications. The presence of fewer contaminants compared to post-consumer PET is advantageous but has the organic blowing agent as a potential problem. The effect of the blowing agent as well as what mechanical properties the agglomerate possesses requires investigation. The exact composition of the agglomerate and the quantity of the blowing agent and if separation between the two is possible should also be evaluated. Additionally, constant supply of the agglomerate needs to be established. The agglomerate is currently recirculated and as the economic analysis proved, it is the most financially beneficial option. However, there is another production facility of the foamed plastics where the yield is lower than 70%, thus all waste produced cannot be recirculated and is instead accumulated. This waste should be the primary focus of selling and establishing a constant delivery of the agglomerate to avoid accumulation. Additional waste is produced but not as regularly, and in big lumps rather than as agglomerate, hence it is more difficult to process and to deliver consistently. Selling the agglomerate is both environmental and economically beneficial. Furthermore, introducing the agglomerate on the recycling market would increase the quantity of non-bottle recycled PET on the market, something the recycling market is need of very much.

To sell the agglomerate as recyclable waste the quality needs to be constant and clearly defined. This can be presented in a form of data sheet containing the most relevant properties of the agglomerate. A suggestion is to include the properties mentioned in Table 7, and additional information about the mechanical properties. Additionally, a comparison between virgin PET and the agglomerate similar to Table 5 would distinctively show the quality of the agglomerate.

The best possibilities for recycling of the agglomerate with respect to recyclability and value lies within the building and construction sector. Because the original product is from the same sector, it is likely similar engineering applications can use the recycled PET. Especially considering the high intrinsic viscosity of the agglomerate. If no suitable applications are found in the mentioned sector, electrical and electronic applications with high value can be possible. However, the recycling rate in this sector is poor because of its difficulties with separation of materials. Furthermore, there are multiple other applications possible but with lower value and lesser possibilities of recycling. Both factors are essential to keep as high as possible to manage the transition towards a circular economy. Additionally, depending of the application the price of the sold agglomerate will vary. The highest price will likely be when sold to the highest value application possible but will probably not exceed much more than half the price of the virgin material. Therefore, it is important to minimize the decrease of the income by choosing a high value application.

A suggestion for easier recycling and a more sustainable process is to exchange the organic blowing agent to a nontoxic compound, for instance carbon dioxide. To have an inert gas as a contaminant instead of a flammable organic compound would increase the value of the agglomerate. Furthermore, when possible the raw material should be changed to recycled and renewable feedstock. However, this is difficult today because of the low quantities of high-quality recycled PET on the market and small production of biobased PET but with an increase in circular flows both alternatives are hopefully more readily available in a few years.

6 Conclusion

The market analysis presented show that the transition towards a circular economy is going slowly with PET as one of the most recycled plastics. However, because much of the recycled PET is from PET bottles and goes into other applications than new drinking bottles, there is a need of other types of recycled PET to fill up the required quantity. The most important properties for recycling of PET is the intrinsic viscosity and the melting temperature as well as the quantity and type of contaminants present. For recycled PET to be recyclable the intrinsic viscosity and the melting temperature can only differ a few percent from virgin PET. However, this method requires further investigation and testing to prove its feasibility. Additionally, a constant supply and quality of waste is essential to establish a continuous selling of recyclable PET.

The agglomerate produced by Diab is high quality PET waste with a high intrinsic viscosity and melting temperature comparable with virgin PET, thus fitting in the presented standard. Therefore, the company can use the structure of the important properties discussed and present these in a data sheet to show the recyclability of the agglomerate. To complete the data of properties, mechanical properties and the effect of the organic blowing agent requires further investigation. PET is used in numerous applications and a wide variety of sector, but it was concluded that the building and construction sector is best suitable for high value applications and good recyclability for the agglomerate. Other sectors are applicable as well but with a considerable decrease in either value or recyclability. Subsequently the price the agglomerate can be sold for decreases with decreased value. If a high value application of the agglomerate is found the agglomerate can hopefully be sold for just over half of the price of virgin PET.

The next step should be to evaluate the effect of the organic blowing agent. Additionally, to establish the mechanical properties and exact composition of the agglomerate. When a data sheet of the agglomerate is in place an investigation of more exact applications of the agglomerate should be made. Furthermore, a full economic analysis is required to evaluate the different cases properly.

To further increase the recycling market several barriers need to be resolved. One of them being standardization and as much as research can be made within the area, clearer regulations within the area is required. Additionally, the approach of plastic production needs to change towards a mindset with recycling in focus. With increased recycling, utilization of the limited resources can be minimized and the transition to a circular economy complete.

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