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Trabajo Fin de Grado

ANÁLISIS DEL RECICLADO DE RESIDUOS INORGÁNICOS EN CANTABRIA: HACIA UNA ECONOMÍA CIRCULAR
(Analysis of the recycling of inorganic waste in Cantabria: towards a circular economy)

Para acceder al Título de

Graduado/a en Ingeniería Química

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1. INTRODUCTION

Nowadays the evident great population growth is linked to the scarcity of natural and mineral resources. This threat is caused by the high consumption of the industrialized countries and its effect is directly shown as impacts to the environment [1].

The circular economy has been proposed as an approach to overcome this problem. The circular economy pushes the frontiers of environmental sustainability by emphasizing the idea of transforming products in such a way that there are workable relationships between ecological systems and economic growth. Therefore, the circular economy is not just concerned with the reduction of the use of the environment as a sink for residuals but rather with the creation of self-sustaining production systems in which materials are used over and over again [2]. The assumed benefits are based on the fundamental observation that the loss of material residuals, in physical units, is minimized.

The economic system is often considered as an open-ended system where production is aimed at producing consumer and capital goods. In turn, capital goods encourage citizens to consume more. The aim of consumption is to satisfy or create ‘‘utility’’ or welfare. When wastes derived from this system are recycled back to resources that will yield new goods, the economy becomes circular [3].

A circular system may be based on both open-loop and closed-loop subsystems. **Open-loop supply chains** consist in materials recovered by parties other than the original producers who can reuse these materials or products. On the other hand, **closed-loop supply chains** deal with the practice of taking back products from customers and returning them to the original manufacturer for the recovery of added value by reusing the whole product or part of it [2].

One clear example of a circular economic system is the production of corrugated packaging. The European Federation of Corrugated Board Manufactures (FEFCO) propose a Corrugated packaging that is 100 % recyclable and biodegradable, which means it is 100 % circular. The new fibers used in the production process are harvested from sustainably managed forests. This way, fibers can be recycled continuously, based on renewable sources. Furthermore, this product counts with a well-established market for secondary raw materials [4,5].

It is necessary to point out that sometimes there is another possibility; reuse. Reuse not only provides a new use of the original product with the same function for which it was produced, but there are also original manners to reuse the products for completely different functions. For instance, this is the case of packaging plastic waste, such as plastic bottles. Unfortunately, reuse can be adopted in only a limited range of applications.

Then, the transition towards a circular economy is mainly about closing the resource loop on materials, but it also provides a reduction of our reliance on natural resources and fossil fuel power generation [4].

As shown in figure 1, the circularity of a given economic system stems from the link between resource processing and waste upgrading [6]. Thus, the design of integrated waste management systems (WMSs) based on waste diversion and waste minimization are the most efficient and cost-effective strategies to achieve a circular economy [2].

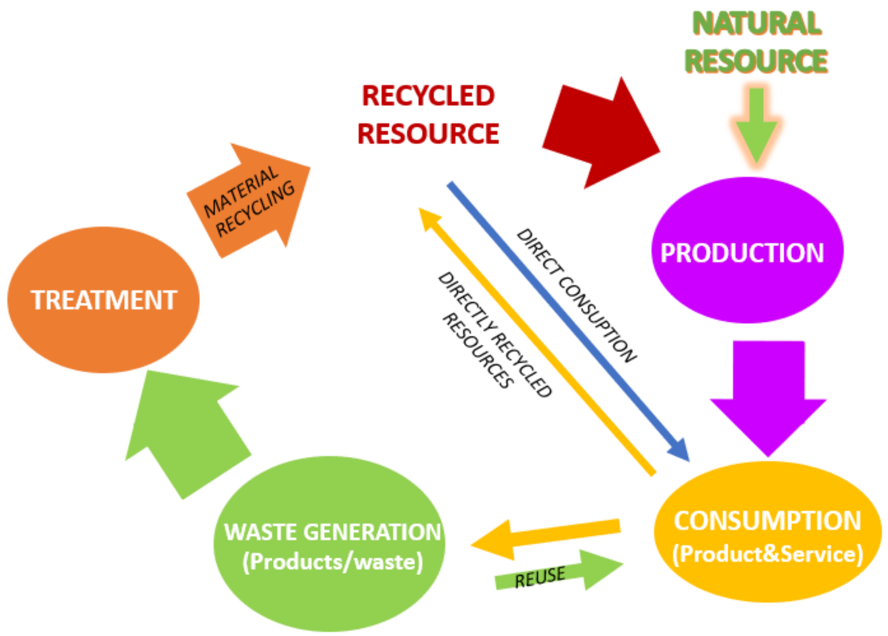

Figure 1. *Overview of a circular economic system*

A waste management system (WMS) encompasses all activities such as collection, transportation, treatment, and disposal as much as solid waste as sewage or garbage. A WMS includes the management of all processes and resources for a suitable handling of wastes materials, from maintenance of waste transport trucks and dumping facilities to compliance with health codes and environmental regulations [2,3,7].

This work focuses on municipal solid waste, (MSW), that is to say, the waste generated by citizens and managed by municipalities. Paper, plastic, textiles, wood, glass, or metals may be found in MSW, but also construction and demolition waste among others [1,7]. Therefore, knowledge of the waste composition and volume, which are directly linked to the local conditions, population, urbanization, and affluence, is fundamental to plan the correct waste management strategies [8]. Current global MSW generation levels are approximately 1.3 billion ton/y [1].

Regarding the environmental concerns and the compliance with regulations related to waste management within the European Union, there are several policy objectives that must be achieved in the upcoming years [9]. They are dictated by the following Directives:

- The 7th EAP of the EC will be guiding European environment policy until 2020 [10]
- Directive 2008/98/EC on Waste [11]
- Directive 1999/31/EC on the landfill of waste [12]

The goal of Directive 2008/98/EC is to decouple economic growth from the environmental impacts associated with waste generation, by recycling **50%** of the household waste (paper, glass, metal and plastics) before 2020 [9,10].More restrictive targets have been set by the European Commission for year 2030:

- **Recycling 65% of municipal waste**
- **Recycling 75% of packaging waste**.
- A binding landfill target to **reduce landfill to maximum of 10% of municipal waste** [10,13]**.**

1.1. CASE STUDY OF CANTABRIA

This project focuses on the Cantabria Region and more specifically, on the materials recoved in the Waste Management Plant of Meruelo. Cantabria is a coastal region of the Northern part of Spain. It has a total area of 5.321 Km^2 and around 586.206 inhabitants. It is administratively constituted by 102 municipalities which generate annually approximately 245.000 tons per year [14,15].

Following Directive 2008/98/EC on waste (EC, 2008), some of the Policy Objectives in 2020 in Cantabria, established by the 2017-2023 Cantabria Regional Waste Plan (BOC 2016), are the following:

- A yearly reduction of **1%** in the MSW **generation**.
- **50%** of **reutilization and recycling**; including 2% of textile waste reutilization, furniture and other susceptible wastes.
- To limit the discharge in landfill to **35%** of the **biodegradable waste generated in 1995**.
- The promotion of re-use in the domestic and commercial areas of certain objects (such as books, furniture, and textiles).
- To achieve **50 % collection of portable batteries** and accumulators as of December 31, 2020 [14].

Table 1 compares the target recycling values from domestic wastes of 2020 with the recycling rates of the region in 2014. Data from the collected mixed waste and also from packaging waste (selective collection) has been used in order to make an estimation about that total amount of materials recycled in 2014 for each relevant fraction waste. As it can be seen, glass and metal are very close to the 2020 target; what is more, the metal value exceeded the proposed target. On the other hand, it is clear that the recovery of plastic is quite far from that required in 2020.

Table 1. Recycling targets for domestic waste for year 2020 and recycling rates in Cantabria (%) in 2014 [14].

Waste fraction	Material recovered 2014 (%)	Objective 2020 (%)
Paper	33	70
Glass	54	60
Metal (Aluminum/Iron)	83	60
Plastic	9	55

MARE, a public company of the Government of Cantabria, holds the environmental management services associated with the maintenance and improvement of the environment. The management of the MSW implemented in Cantabria consists in the treatment of four different waste streams that are collected and managed separately; mixed waste, paper and cardboard, glass packaging and light packaging wastes [9,14].

Although this work focuses on the recovered materials at the Meruelo plant, there are other waste recovery and recycling centers . El Mazo and Candina. Both centers are in Torrelavega and Santander respectively and deal with the sorting and preparation of the wastes in order to subsequently send them to recyclers such as Ecoembes. In addition, it sorts and grinds the bulky items from the selected collection. The inlets are light packings (yellow container) and paper-carboard (blue container) collected selectively in the corresponding municipalities of the region [16].

The Waste Management Plant of Meruelo, which manages the mixed waste stream, is split into two stages: recycling and composting and incineration with energy recovery [17]. The stream of mixed waste is collected in each municipality and transported to a transfer station. From these facilities the mixed waste stream is reloaded onto larger long-distance transport vehicles and it is finally shipped to the Mechanical Biological Treatment (MBT) section. The MBT involves the mechanical sorting of mixed waste into a biodegradable fraction and a reject fraction. The former fraction is composted and the reject fraction is sorted out again to recover materials, obtaining a final fraction that is incinerated. The refuse streams from the MBT, composting and incineration are disposed of in landfill [9,17].

Currently there is not enough information available to the public about what happens to the different materials once they have been separated in Meruelo. That is why an estimation of what would be recovered is made based on the analysis of the recycling technologies.

1.2. AIM OF THE WORK

The main aim of this work is to perform a literature review on the most commonly applied technologies to recycle the inorganic materials found in MSW (plastic, iron, aluminum, glass and paper and cardboard), in order to estimate the amount of secondary materials that can be recovered from the MSW generated in Cantabria and find potential applications for them within the region. To fulfill this general objective, several specific objectives need to be achieved:

- Firstly, it is necessary to gather all the available information regarding what happens to the recovered materials once they have been separated in Meruelo.
- The second objective is to propose different recycling pathways for each waste fraction based on the literature review of the available current technologies.
- Once the recycling routes are proposed, another aim is to estimate the amount of recovered materials based on the selected combination of technologies.
- Finally, in order to complete the information needed to support the main purpose of this project, the opportunities to exchange recycled materials in the region of Cantabria will be studied.

Therefore, this work focuses on the waste treatment stage and the subsequent introduction of the recovered materials into the production systems, which is the cornerstone of the circular economy, as shown in figure 1.

2. METHODOLOGY

The methodology that has been followed in the initial phase of the project is a systematic literature. Articles, journals, engineering web sites, encyclopedias and science reviews have been used to search for the required information. To start the search, headlines such as “paper recycling”, “aluminum recycling”, “aluminum by-products”, “recycling processes in Europe” or “circular economy concept” have been written in the Scopus and Google search engines.

Additionally, the European Pollutant Release and Transfer Register (E-PRTR) data base has also been used, given that this source provides access to the integrated environmental authorization of the industries that could be of interest for the work.

In order to determine which technologies can be applied to recycle the materials recovered in Cantabria, the results of the literature review have been combined with the selection criterion given by the author’s own assumptions. This especially occurs when recycling pathways are created. Most of the reviewed articles do not contain entire recycling routes with specific technologies to apply. Because of that, combinations of possible recycling treatments from different sources have been made, taking in to account the specifications for each unit operation.

On the other hand, all the mass balances have been carried out on an Excel sheet. The flow diagrams that represent the different proposed recycling routes have also been made with this tool.

3. RESULTS AND DISCUSSION.

Plastics, paper and cardboard, glass, aluminum, and iron are the main materials collected in Cantabria due to household wastes [9,14]. Thus, all the results and discussions are carried out according to these waste fractions.

3.1. CURRENT FATE OF THE WASTE FRACTIONS SORTED IN CANTABRIA.

In this section the little available information collected from literature review about the fate of the waste fractions sorted in Cantabria is described. However, there is only available information about the fate of the materials from the selective collection. Since Meruelo only manages the separation of the inorganic material, but does not manage its recycling, different recyclers from other communities take action in this function.

Regarding the Paper and Cardboard waste fraction, its source separation and collection is implemented in all the municipalities of the region and is managed by **Ecoembes** , a non-profit company responsible for its recycling. The P&C collected directly from blue containers is transported to the material recovery facility (MRF) located at Guarnizo, where the different materials are separated. Finally, these separated materials are transported to a recycling company located in **Zaragoza,** 383 km away from Guarnizo [9,18].

Ecovidrio is the non-profit company that manages the glass packaging selective collected sorted in Meruelo. It sends the material to a recycler located in the **Vizcaya** region, 70 km away from the Meruelo Plant. This recycler company is responsible for the installation of containers and infrastructures, the service of collection and transport and the treatment of the residues of glass containers. Once the residues have arrived at the treatment plant, they are introduced in a separation and crushing process. Then the cullets (small fragments of clean glass that serve as raw material) are obtained [9,19].

On the other hand, the light packaging waste from households, placed in yellow containers, is also collected by **Ecoembes** as well as transported to two MRF plants where the different materials are sorted. These materials are sent individually to the recycler, located in the region of **Navarra,** 240 km away, through a transfer station [9,18].

3.2. DESCRIPTION OF RECYCLING TECHNOLOGIES

The management of the different waste fractions is one of the most debated issues in the literature on integrated MSW management systems. Then, this project contributes to this debate by providing alternative waste recovery routes.

It is assumed that the recycling plan for all the waste fractions follows the same structure or has practically the same stages as those shown in figure 2, although the order may differ:

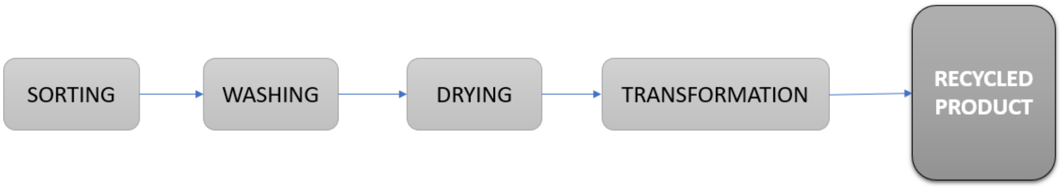

Figure 2. *General recycling scheme*

However, it is evident that there are differences depending on the material to be recycled. Thus, in this section a flow diagram is proposed with its pertinent mass balance for each residue fraction, assuming **1 Ton** inlet.

3.2.1 PLASTIC RECYCLING.

Plastic constitutes an increasingly important fraction of municipal solid waste. In fact, MSW is the main source of waste plastics, whereas the second waste plastic stream comes from the distribution and industrial sectors [20,21]. The plastic waste stream arrives to the recycling chain as a mixed plastic bale. The generic composition of plastic includes Polypropylene (PP), Polyethylene (PE), Polyethylene terephthalate (PET), Polyurethane (PU) and plastics films. Thus, plastic recovery must necessarily include the large-scale use of various recycling techniques [21]. More than 64% of the total plastics waste is valorized via mechanical recycling in Europe [22].

Figure 3 shows the proposed recycling route for the plastics fraction. The composition of the plastic stream (Table 4 in Annex I) is assumed from the Cantabria Waste management plan [14].

PP, PE, PET and PVC are assembled since the three fractions follow the structure of figure 2. Nevertheless, film and PU are described separately because they have a slightly different process.

a. PP,PE , PET and PVC:

SORTING

The first piece of equipment suggested to pre-sort the bale form that arrives to the recycling chain is a **debaler** [23,24]. A debaler allows baled or loose input material to be fed into manual pre-sort cabin [25]. Then, wastes pass through a **manual sorting** and **ballistic separator,** which mainly produces a rigid film as output. Although manual sorting is probably a very rudimentary technique, it is impossible to avoid it in this type of chains [26].

Optical scanners or other advance methods could be added, but in this case manual sorting is the preferred technique to make easier PVC and PU sorting stage. Operatives manually remove non-packaging plastics and non-plastic items, mostly paper and cans. If there is excessive amount of metal items mixed with plastic fraction an **eddy current separator** is proposed. This method is specifically for the separation of metals. The principle is based on the induction of a current into a conductor by changes in magnetic flux cutting through it. Then, a combined driving and repelling force is applied which ejects the conducting particle from the product stream [1,22].

The Sorting step ends with the application of **Near Infrared Sensor** (NIR). This sorting technique works illuminating with halogen lamps and analyzing the reflected light. The principle is the materials property of absorbing light at characteristic wavelengths determined by the specific material molecular structure [1].

Therefore, the remaining rigid mixed plastics enter a series of four NIR sorting units. Firstly, is removed PP, followed by PET, PE and PVC. It is assumed that clear PET bottles are removed previously manually from the eject fraction [22].

<u>WHASING AND DRYING</u>:

This step consists basically in a washing and drying line. However, **washing** refers to the pre-washing stage which is the beginning of the washing line. Both washing stages are executed with water, **employing caustic** soda and **surfactants** for glue removal from plastics [23]. Labels and stickers are the mainly residues rejected, so the water is agitated, which forces the material to rub against itself, helping to break down paper labels, loosen dirt and remove other forms of contamination [24,26].

The latest generation of wash plants use only between 2 and 3 m^3 of water per ton of material. Advances in technology allow to save about one-half of water as opposed to previous equipment [26].

Finally, the conventional way to dry after washing step is by heat adapting temperature to each fraction composition.

On the other hand, an innovative technology for the removal of organics and surface contaminants from flakes, named **dry-cleaning,** could be considered. This technique cleans surfaces through friction without using water [26].

FURTHER SEPARATION

A further separation is carried out after washing stage. In this case, through **Sink/float separation** HDPE an LDPE recovery from PE is achieved. Additionally, this application is also placed in *PP* and *PVC* chain because can effectively separate polyolefins from these fractions. In this way it is acquired high purity product results. What is occurred into floating tank is a separation basing on densities [22,26].

TRANSFORMATION:

It is complicated to pinpoint a specific process for all the fractions because the techniques vary according to the type of polymer. The technologies shown in Figure 3 are described here.

PP and PE: **Fine screening** and **extrusion of fine and coarse** is applied. Both techniques are involved in size reduction step. The plastic is extruded to strands and then pelletized to produce a single-polymer plastic [21].

PET it is sent to a **Shredder** to cute large plastic parts by shear or saw for further processing into chopped small flakes [24]. Cleaned flakes are brought to a **float sink** (HDPE recovery), then, **bagged** and sold as flake.

PVC is also shredded into pieces of 10-15 cm or can be shredded into smaller pieces to produce powder as it is shown in figure 4.

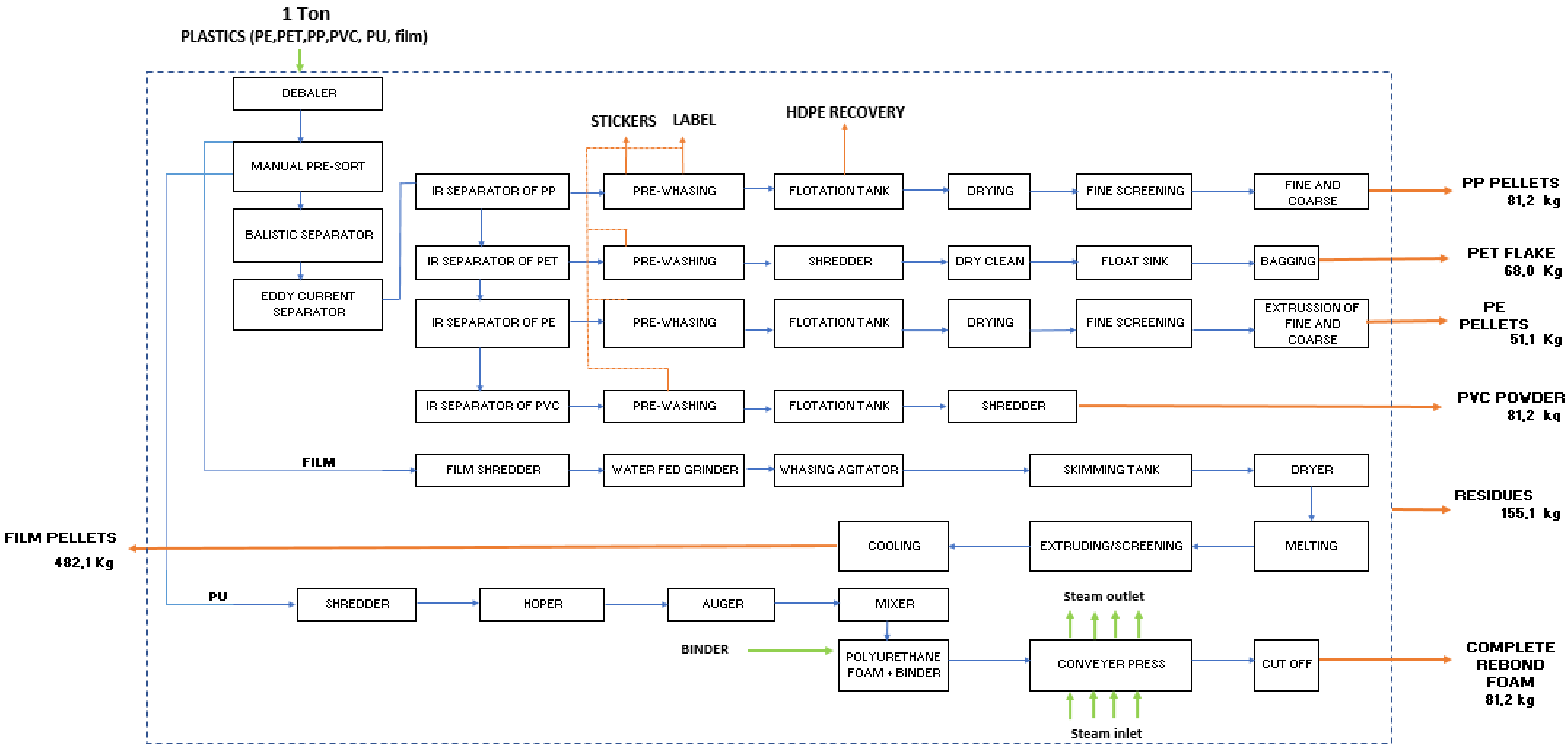

Figure 3. *Plastic recycling flow diagram*

a. FILM:

Film plastic does not fulfil figure 2, since, washing step is preceded by transform stage. This is because grinding is necessary to get film into a form in which it is easier to wash and extrude. Therefore, film is fed into a **shredder** to make it more manageable and then fed into a **water-fed grinder** where it is reduced to pieces that measure about one-half of 2.54 cm in size. After grinding, the film is conveyed again into **washing** equipment. The plastic film, which is lighter and tends to float toward the surface, is skimmed off in the **skimming Tank** and brought to a **dryer**. Once dry, the clean, ground film flake is **melted** in a furnace and **extruded** through **screens** that are used to filter out any remaining impurities. This is the point at which pellets are produced and cooled (with either water or air) so they can then be used in manufacturing [24,27].

a. PU:

The PU recycling line shown in figure 3, is known as *rebounding-process.* PU fraction waste is manual pre-sorted, then it is **shredded** and is fed to an **auger** by a **hopper**. After that, 10 % binder is **shredded** with to the 90 % of scrap and the mixture is then **compressed**. In the conveyor press is introduced steam to help in this function.

The rebound process has been selected because incorporates high flexibility and a wide variability in the mechanical properties of the final product, foam blocks [26].

3.2.2. PAPER RECYCLING.

Cardboard should be recycled separately from paper due to its characteristics (i.e. stiffness, hardness), which may slow down the process of paper reprocessing [28]. Only an inlet composition below 2% cardboard is allowed in the paper recycling process.

Nevertheless, cardboard can follow the route proposed for paper recycling and paper can be used in the cardboard recycling process without any inconvenience. According to industrial experts, the sorted cardboard fraction still contains roughly 7% of postconsumer paper attributed to imperfect sorting. What is more, recycled paper provides 88% of the raw material for the production of new corrugated boxes.

In addition to that, recycling cardboard and paper consumes less energy and causes fewer emissions than manufacturing the same quantity of paper from virgin resources.

The actual savings will depend on the technology used for the reprocessing of paper and its emissions, source and amount of energy used, etc. [29].

In this project the term recycling covers the combination of a waste paper reprocessing technologies and the addition of this recycled paper to the conventional process of paper manufacturing, as it is shown in Figure 4. The different stages of the process are described in this section.

SORTING

Once collected, the mixed waste passes over a rolling drum with paddles or cams. Because the P&C is lighter and flatter than other wastes, it is propelled forward and the heavier, more dimensional materials fall out behind the drum [30].

TRANSFORMATION 1

The transformation of the waste P&C is the second step. A washing stage is implemented prior to **pulping**. Through pulping, paper is disintegrated into individual fibers dispersed in water. It may be a batch or continuous process [31].

FURTHER SEPARATION

The next task is to remove contaminants. **Screening** is proposed to remove relatively large amounts ink and contaminants from the pulp slurry. Particles from the shredder go through different lines depending on the size of the expected print particles [32].

When ink touches the surface of paper, pigment particles are absorbed creating **print particles,** which must be removed for paper reprocessing. Filters, centrifugal cleaners, flotation cleaners and washing are used in combination to separate the ink from the fibers, as shown in Figure 4.

Centrifugal cleaners work for particles between 0.1 and 0.4 mm, which may include some toner and large pigment print, but it is aimed at other contaminants. Furthermore, it spins the fibers, water and ink causing particles with different densities to move towards the outside of the spinning water at different rates.

This allows to separate cellulose from other materials with different density [32,33].

Flotation dilutes pulp again to around 1–3% pulp per unit of water and then passes air bubbles through it. A dirty foam is created due to the air bubbles, which attract some print and dirt particles preferentially and carry them to the top of the water. This foam is **scraped off** and disposed of. The process can be aided with the use of surfactants. Regarding particle size, it is for particles 0.05–0.15mm, which tend to include most toner print [33].

The **washing** unit operation is used for particles below 50 µm and water-soluble inks. Particles pass through a fine screen while the water flows at the same time taking very small contaminants and water-soluble print with it and leaving the clean fibers.

The size of the print particles can be reduced by dispersion or increased by agglomeration. **Agglomeration** uses chemicals, usually a combination of solvent and **surfactant**, to cause ink particles to compact larger clusters allowing them to be more easily filtered, whereas **dispersion** uses surfactants or shear forces to break the ink into smaller particles. This is done either to ease washing or to make any remaining print indistinguishable to the human eye. Both agglomeration and dispersion are carried out at 60–80 ◦C temperature operation in order to soften toner print particle [31].

<u>TRANSFORMATION 2</u>

Once the pulp is free of contaminants, it is sent to the *conventional paper making process*. **Bleaching** is the first unit operation. The use of hydrogen peroxide is proposed in figure 4, although other chemicals such as oxygen or ozone can be used in order to whiten the pulp. **Forming** consists in pouring water over molding systems to be **pressed** on to meshes to form flat sheets. Then, the resulting product is dried in a hot drum, **cut** and passed through a **calender** to obtain a glossy finish in the final the product, which is finally packaged and prepared to be transported [30,31].

3.2.3. ALUMINUM RECYCLING

Primary production of aluminum is based on bauxite mining, which is treated and later processed into metallic aluminum through electrolytic reduction. The recycling process simply involves re-melting the metal, which is far less expensive and energy intensive than creating new aluminum through electrolysis of aluminum oxide [34]. In fact, recycled aluminum uses 5 % of the energy that would be needed to create the equivalent amount from raw materials. Moreover, the purpose of using scrap is not only to save raw materials, but also to avoid the costs of buying metal. This way manufacturers and industries can reuse some of their wastes and save money [35].

Figures 5 and 6 show two alternatives to aluminum recycling. Figure 5 considers to bring scrap back to the conventional manufacturing process whereas figure 6 is an alternative route to transform aluminum alloy scrap lost in manufacturing operations, into objects with definitive cross-sectional profile for a wide range of uses (hot extrusion). However, the later can be applied to all the aluminum pieces that are mixed with the rest of the residues and thrown away. Because of that, it is considered in this work.

1st route: *CONVENTIONAL ALUMINUM PRODUCTION PROCESS (red lines in figure 5)*.

SORTING:

Following the conventional recycling scheme, aluminum recycling starts with the sorting stage. **Manual sorting** is included in combination with the **eddy current separation technology**. The sorted products fall into separate trays to be recycled in different ways. However, in this case, it is assumed that all aluminum fractions pass the same recycling route without making distinctions between cans or other aluminum items.

TRANSFORMATION 1.

The collected wastes are **crushed** obtaining aluminum pieces, then, these particles are **liquefied** and **thinned** into a mold.

WASHING (Purification).

The extent and nature of foreign materials in the scrap depend on the efficiency of the sorting techniques. However, aluminum scrap can be also contaminated by pollutants and substances. A variety of chemical methods are currently used to remove emulsion from the scrap, but they are usually too expensive and produce more environmental pollution. In this recycling route, it is assumed that **chlorine** is used for **purification** [35,36].

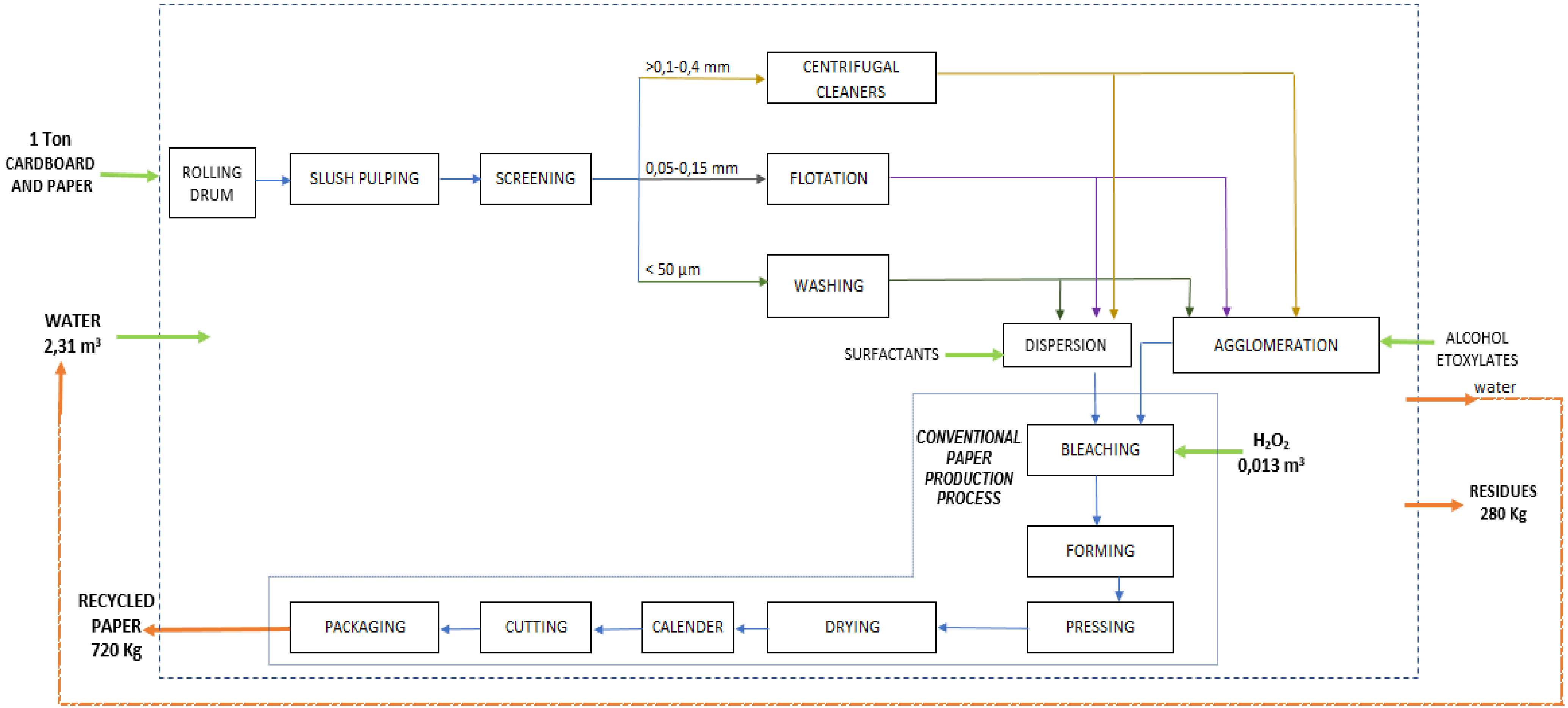

Figure 4. *Paper and Cardboard recycling flowdiagram*

TRANSFORMATION 2.

Once the scrap is clean enough and purified, it can be incorporated to the conventional aluminum production process. The red chart in Figure 5 delimits a simplified view of this process with its most important operation units [37]. At this point more substances would be added to the raw material, but it is not of interest to this project, so only the melting furnace and the holding furnace are shown in the figure.

The **melting furnace,** as its name implies, melts the aluminum. Moreover, the melting of the clean material can save energy and reduce the generation of skimmings /dross. Skimmings/dross are by-products that conform an oxide layer. This happens because aluminum is easily oxidized.

The metal is refined or turned into an alloy in a **holding furnace**, where gases and other metals are removed. For instance, magnesium and other impurities can be present in secondary aluminum and they may also need to be reduced. To remove magnesium, molten aluminum is treated with chlorine gas mixtures but sodium aluminum fluoride and potassium aluminum fluoride can also be used. After this treatment in the holding furnace, another by-product is created, which is skimmed from the metal surface before casting.

The last stage is the **casting** unit operation. Casting is performed with water-cooled metal moulds and a holding table at the bottom of the moulds. Aluminum is placed over them, forming large ingots, billets, and slabs. Billets and slabs with smaller cross-sections can also be produced by horizontal direct chill casting. There are also other casting methods such as the continuous casting of thin sheets as well as wire rod. Along the process additional small quantities of dross are also produced but they are removed from the surface of the molten metal [36,37].

2nd route: *NEW ALTERNATIVE ALUMINUM RECYCLING (Figure 5, brown lines*).

This second proposed route follows the same steps than the previous one until the *TRANSFORMATION 2*.

There are more options to purify aluminum than the use of chemicals. One of them is purifying the metal by **thermal methods**, with the benefit that the thermal cleaning process is carried out without the carburization of scrap deposition [36].

It is important to point out that the purification of the metal as well as its recycling is a line of research with very few data and for that reason it has a recycling approach more limited than the rest.

TRANSFORMATION.

Due to the previous stages, mostly crushing operations, the hardness of the aluminum has been slightly increased. Because of that, the granulated scrap needs to be under low pressure to soften the aluminum particles. This process is known as **annealing** and it is carried out in a muffle furnace under a controlled atmosphere at a super saturation temperature range, 490-505 ºC.

WASHING 2.

After the annealing operation, the surface oxides need to be removed from the aluminum particles. This **cleaning** operation is performed in a **bath of sodium hydroxide** at 65-77 ºC.

DRYING.

The drying stage occurs in ovens at 80-100 ºC. Once the granulated aluminum is dried, the final product is prepared [36].

3rd route: *HOT EXTRUSION (Figure 6)*.

The hot extrusion process does not follow the conventional recycling scheme (figure2). The aluminum extrusion process starts with a **pre-heating** step. Since the die has openings, pre-heating is proposed to prevent the aluminum from sticking in these openings. The heating furnace works at 482.22 ºC, an adequate temperature to allow the billet to become soft and still maintain its shape in a solid form. Next, the die is loaded into the press as a billet. While **extrusion** occurs, the heat from the billet is transferred to the press and the billet is crushed against the dye. The pressure continues increasing, and the aluminum begins to squeeze out through the opening of the die to emerge on the other side as a fully formed profile. Then, extrusion is **cooled** either naturally or with water quenchers. Cooling occurs in a cooling table. A **stretcher** is used after the profile has been cooled to smooth the piece. Figure 7 shows the entire process better.

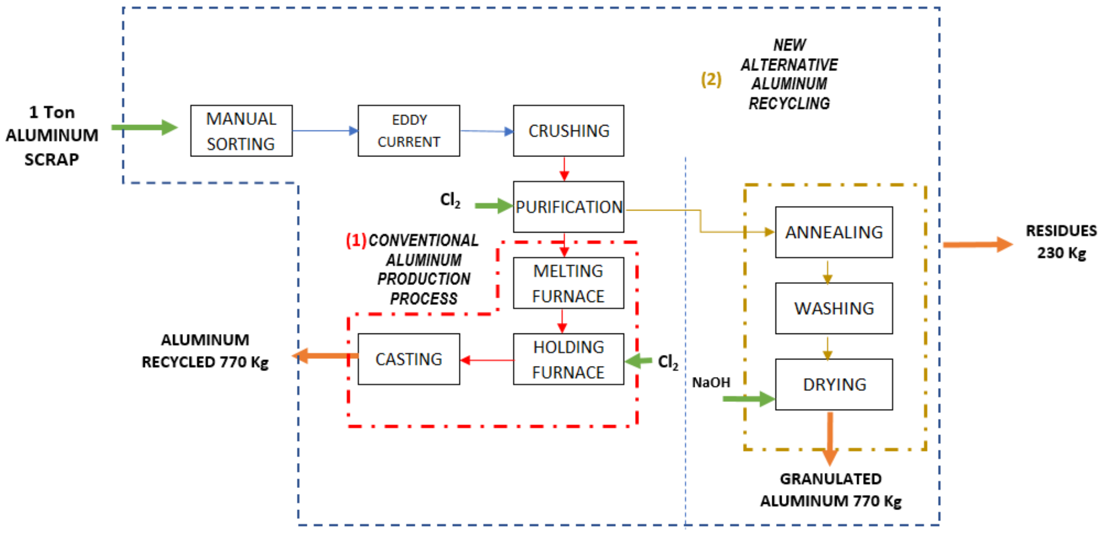

Figure 5. *Aluminum recycling flow diagram, Routes 1 and 2*.

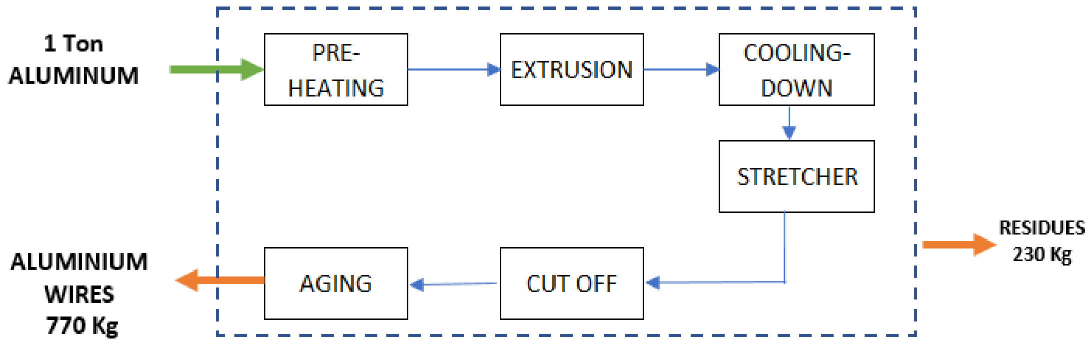

Figure 6. *Aluminum recycling flow diagram, Route 3: Hot extrusion process.*

A finish **cut off** is used to cut the profile to the specified commercial item. Extrusion alloys reach their optimal strength through the process of aging, sometimes known as age hardening, which occurs at room temperature. Artificial aging takes place through controlled heating. Once the extrusion process is complete the die is removed from the press and cleaned of any residual aluminum. After being cleaned, the die is inspected and prepared for the next time it will be used to extrude this profile [35].

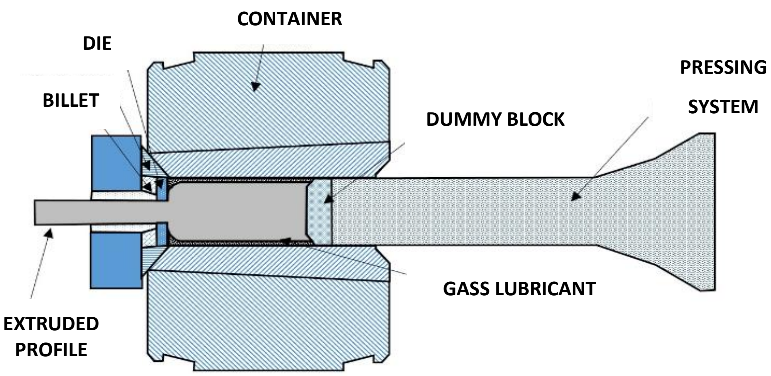

Figure 7. *Ilustration of the extrusion process*

3.2.4 IRON RECYCLING

The primary consumers of ferrous scrap are the iron and steel mills and foundries. Minor consumers could be ferro alloy producers or even copper producers for use in copper precipitation and the chemical industry. The steel industry consumes about three-fourths of the total scrap, whereas the scrap consumption of ferro alloys production, copper precipitation, and the chemical industry represent less than one million ton [37].

In the recent past a lot of scrap was lost along the steel-making process. However, the current use of electric furnaces (EAF) and basic oxygen furnaces (BOF) decrease the waste of iron [38]. Production of steel from scrap consumes considerably less energy compared to the production of steel from iron ores. However, the problems with the quality of scrap-based steel introduce restraints to its use.

Figure 8 shows the four routes that are currently used worldwide in the production of steel. The classic blast furnace / basic oxygen furnace route, the direct melting of scrap (electric arc furnace, EAF's), smelting reduction, and direct reduction. However, these routes belong to the conventional steel manufacturing process, and only the main unit operations are drawn. What is relevant to this work is the second chart in Figure 8, where the EAF's and the O2-converter are depicted BOF.

EAF's is used after the direct reduction of iron ores as well as for the direct melting of scrap, whereas BOF is used in the Classic Blast Furnace and the smelting reduction routes. Therefore, as figure 8 shows, scrap is directly added to the EAF's or to the BOF.

It is important to point out that 1 ton of scrap enters the recycling process, not the conventional process, and it is assumed that the ton of scrap goes into each route separately, although it is represented combined. In the same way the efficiency is assumed equal for all the routes and 0.91 ton are referred to each pathway.

ELECTRIC ARC FURNACE

The EAF governs the melting period. Melting is accomplished by supplying energy to the furnace interior. This technique consists in placing the iron scrap directly into an EAF where materials are smelted (direct melting of scrap). It operates as a batch melting process producing batches of molten steel known "heats". The EAF requires a considerable amount of electrical energy and causes substantial emissions to air and solid process residues such as slags and dust. The emissions to air from the furnace consist of a wide range of inorganic compounds (iron oxide dust and heavy metals) and organic compounds such as persistent organic pollutants [38,39].

On the other hand, this type of furnaces is also used after the direct reduction process, which involves the production of solid primary iron from iron ores and a reducing agent (e.g. natural gas). The solid product is called direct reduced iron (DRI) and is then applied as feedstock to an EAF where Iron is transformed into Steel by the same melting process [39].

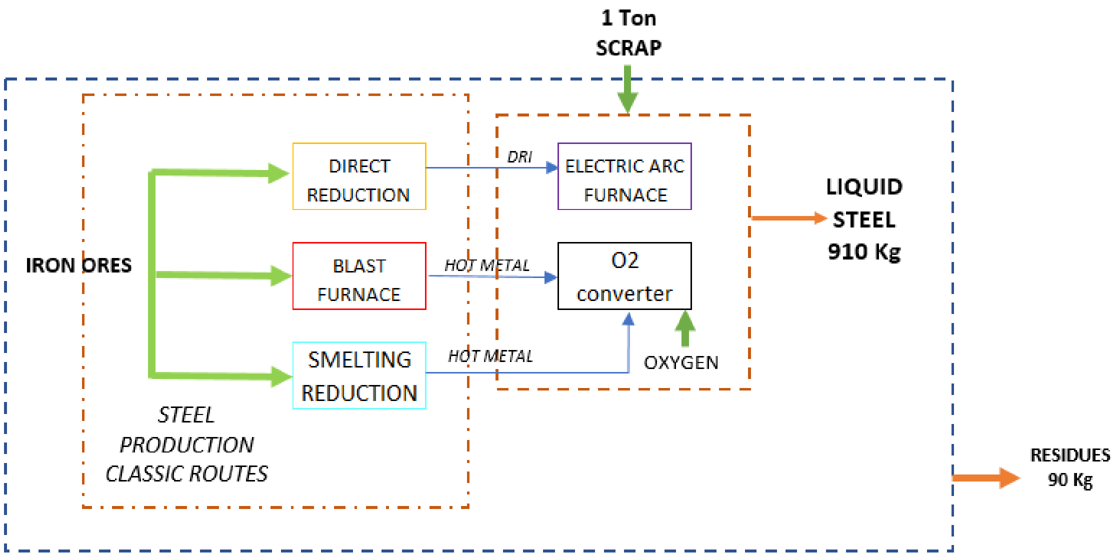

Figure 8. *Iron scrap recycling flow diagram*

BASIC OXYGEN FURNACE

The BOF, also named O2- converter (figure 8) is a steel making furnace, in which molten pig iron and **steel scrap** convert into steel due to oxidizing action of oxygen blown into the melt under a basic slag [38]. Basic Oxygen Steelmaking process differs from the EAF in that it is autogenous, or self-sufficient in energy. The primary raw materials for the BOF are 70-80% liquid hot metal from the blast furnace and is steel scrap [39].

Regarding figure 8, blast furnaces require coke, and coke plants are expensive and have many environmental problems associated with their operation due to the oxidizing action of oxygen blown into the melt under a basic slag [38]. Then, after this unit operation, the scrap is added to the BOF.

3.2.5. GLASS RECYCLING

Glass is a major fraction in MSW [40]. Glass is a homogenous, non-crystalline material with properties that provide several attributes for many commercial products [41]. It can be found mainly as container glass for beverages and food but it also appears as ruble from construction. Glass manufactures obtain many benefits increasing the recycling content in glass products. In fact, glass manufacturing plants receive the cullet from the waste industry and use it as feedstock in glass production instead of the conventional raw material. By using 1 ton of recycled glass to make new glass, instead of using raw materials, 1.2 tons of virgin raw materials are saved [40,42].

It is important to point out that glass containers, re-usable bottles are usually handled by separate return-and-deposit systems, organized by a specific company. However, in this study re-usable bottles collected by waste management systems and recovered from waste are considered.

This study assumes that nothing goes through route 1 (figure 10) since it is not a recycling route per se. Therefore, the results for the mass balance correspond to route 2. The market can be classified according two uses: (1) reuse of glass containers and (2) recycling (figure 10). Methods for reuse and recycling container glass and waste glass (cullets) are considered bellow.

***(1) Reuse of glass containers**.*

<u>SORTING</u>

Imaging sorters have four main components: the feed system, the imaging system, imaging processing software and the separation system.

Firstly, the waste enters the system and is spread into a uniform monolayer. This way, wastes are presented correctly to the imaging system avoiding clumps. Then, all the items are inspected by lights and sensors from the imaging system and all of them are compared using accept/reject criteria depending on the type of waste. Those residues that do not meet the specifications (ceramics, plastics, metals…), are separated using compressed air for small products and mechanical devices for larger size items. This way, conventional screen bars for cullets can be substituted [1].

The second unit operation in the sorting stage is the **magnetic separator**. Although the previous technique should reject most contaminants presenting in the inlet stream, the further separation of metals should ensure a better sorting efficacy.
At this point of the recycling chain, re-usable bottles and non-reusable bottles with cullets continue in different operation lines. Because of that, it is necessary to include a **manual sorting** after the magnetic separator to decide which bottles can be re-use and which do not meet the requirements.

After that, another sorting technique, the **Brown Green White color separator** separates the bottles according to colors. Other colors such as blue, red, yellow, etc. can be sorted out as separate colors, or “grouped” with one of the main three colors. It’s all up to the operator to decide [43,44].

<u>WASHING</u>

Once there are only entire bottles in the operation line, they are **washed** with hot water and soda to remove all labels.

<u>DRYING</u>

Then, clean bottles are **dried** either naturally or with air, and finally packaged.

(2) Recycling

SORTING

Following route 2, cullets are crushed in screen bars to reject big particles. Next, an optical scanner is used to separate the cullets by colors.

TRANSFORMATION

Once there are different cullet fractions according to their colors, each one is **crushed** and incorporated to the conventional glass manufacturing process. This process starts with the re-melting of glass. The melting process releases carbon dioxide; the main component of glass (silica) is oxidized, and up to 20% of the its mass is lost as gases [40].

The melted glass is taken out of the furnace and shaped. However, until the required product is achieved (depending on the manufacturer's desires), several steps of heating and cooling of the material are necessary, none of them has been included in the flow diagram.

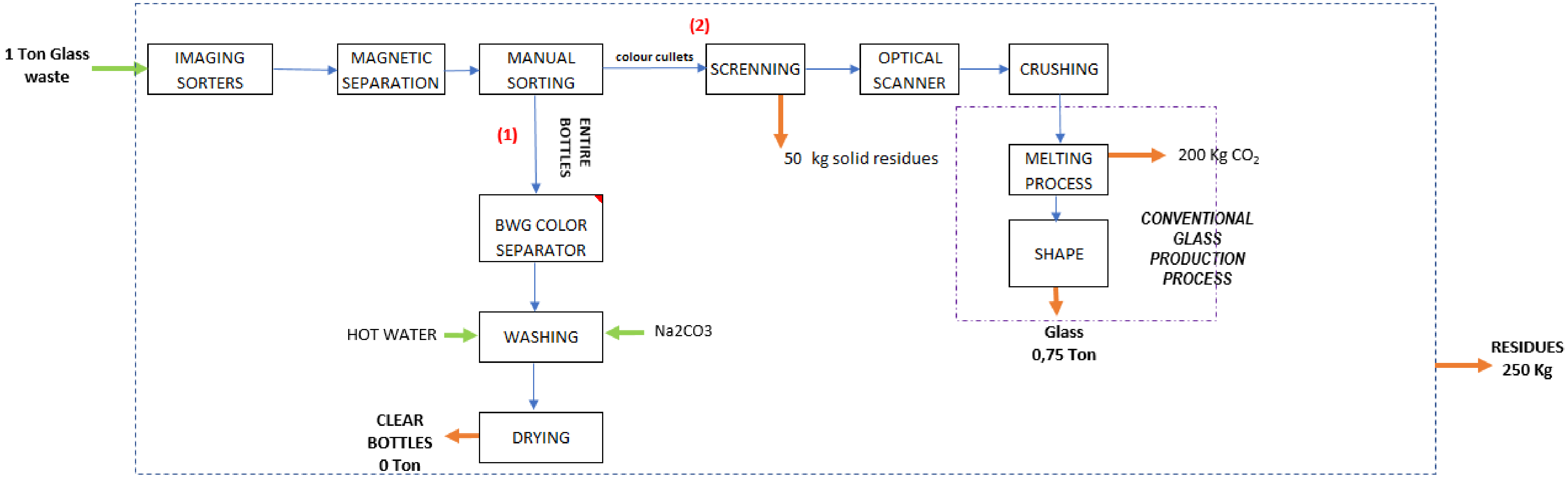

Figure 9. *Glass recycling flow diagram*

3.3. ESTIMATION OF THE RECOVERED MATERIALS

An estimation of the amount of materials that can actually be recycled from the waste streams that are sorted in the Meruelo plant is provided in this section. To do so, the mass balances performed were based on the flow diagrams described in the previous section, and the efficiencies of each process were taken from the literature. **Annex I** includes all the tables that gather the required data used for the calculations (efficiencies of the recycling technologies, and waste quantities and composition).

The film recycling efficiency derives from the assumption that most film is PE, then the same value is taken. For the other fractions, an average from PET ad PEAD efficiency has been assumed.

Table 2: Recycled plastics and residue after treatment

	INPUT (ton)	**OUTPUT (ton)**	
		RECYCLED MAT.	RESIDUE
PET	74	56	18
PEAD	48	42	6
FILM	451	397	54
Others (PU/PVC/PP)	251	201	50
TOTAL	823	695	128

On the other hand, the PU, PVC and PP compositions in the plastic stream recovered from Meruelo is not quantified. Due to this lack of information the fraction composition value referred to "others" in "Plan de Residuos de Cantabria 2017-2023" is assumed to be composed of these three fractions in equal amounts. Finally, the efficiency obtained for the Iron recycling process is 91%. This value was calculated as the efficiency of an iron production process that consumes both scrap and iron ore.

Table 3: Recycled Paper, Aluminum, Glass and Iron and residue after treatment**.**

FRACTION WASTE	INPUT (ton)	OUTPUT (ton)	
		RECYCLED MAT.	RESIDUE
PAPER	6645	4784,40	1860,60
AL	6438	4957,26	1480,74
IRON	6438	5858,58	579,42
GLASS	475	356,25	118,75

3.4. POSSIBLE EXCHANGES OF MATERIALS WITHIN THE REGION OF CANTABRIA

A list of industries that could benefit from the purchase of the recycled materials that are recovered from the mixed waste generated in Cantabria has been compiled. To do so, the integrated environmental authorizations of several industries that consume the raw materials present in the studied waste fractions have been reviewed.

Table 4 shows the industries that have been selected. This table collects data such as the total production per year, type of manufacturing product and the needed raw materials.

A cross in the last column indicate that those companies already incorporate recycled material to its production process. As it can be seen, most of them use secondary materials, mainly foundry metals, but the percentage of recovered material could probably increase. In addition to that, all those industries that consider recycled material do that only in an internal form. That is, they do not use secondary materials that come from MSW as this study proposes, but secondary materials from their own production processes.

On the other hand, there are industries such as CELLTECH, Mecanizados Norte Bravo or Talleres Oran that do not consider this possibility. They only do not include secondary materials in their manufacturing processes, but they are also not benefiting from the other advantages of a circular economic system.

For instance, CELLTECH produces around 6000 ton/year of paper while approximately 4000 ton/year of paper can be recycled in Cantabria (Table 3). Thus, a significant fraction of the paper recovered in Cantabria could have the potential to be applied in this regional paper production process. However, around 800 annual tons of plastic could be recovered from the mixed waste, while ASPLA produces 95000 ton/year approximately. As it can be seen, there is a large difference between both amounts, so the introduction of recycled plastic in this particular industry may be insignificant.

Table 4. *Industrial production in Cantabria obtained from the E-PRTR database*

	PRODUCT	AMOUNT	UNITS	RAW MATERIAL	USE OF SECONDARY MATERIALS	
					YES	NO
ASPLA	Plastic packaging and containers	95.000	ton/year	Polyethilene (plastic)		x
BOSH EECTRODOMÉSTICOS	Portable stove, cupboard,countertop and stove	611.000	units/year	Aluminium and ferrous plates		x
CELLTECH	Paper paste	6.000	ton/year	Eucalyptus wood		x
FUNDICIÓN CARG	Grey iron	6.000	ton/year	Iron	x	
GLOBAL STEEL	Bars of iron and thick wires	2.000.000	ton/year	Iron ore and scrap	x	
GREYCO	Smelting ferrous metas	28.000	ton/year	Aluminium and iron	x	
INDUSTRIAS HERGOM	Smelting of laminar grey iron	48.000	ton/year	Iron, iron alloys and Scrap	x	
MECANIZADOS NORTE BRAVO	Smelting of machining pieces and aluminium machining	30.000	ton/year	Aluminium		x
NISSAN MOTOR IBÉRICA	Castings and machining parts	200.000	ton/year	Iron	x	
SAINT GOBAIN CANALIZACIÓN	Ductil cast iron pipes	300.000	ton/year	Iron, Iron alloys and Scrap	x	
SIDENOR INDUSTRIAL	Iron	269.000	ton/year	Iron, Iron alloys and Scrap	x	
TALLERES ORAN	Bodywork pieces	30.500	ton/year	Iron plates and Iron alloys		x
TYCSA	Prestressed wire , laces and steel wires	135.000	ton/year	Iron (wire rod)	x	

4. CONCLUSIONS

This project contributes to the idea of establishing the concept of a circular economy in the Cantabria region through the recycling of inorganic solid waste and the recovery of this wastes as secondary materials. For this purpose, a literature review on the most commonly applied technologies is performed to estimate the amount of secondary materials that can be recovered from the MSW and find potential applications for them within the region.

The results are subject to a number of assumptions and approximations; thus, an uncertainty analysis could be useful to determine the accuracy of the results. However, it provides insightful conclusions that might lead to further investigations in this field.

On the one hand, public information about what happens to the waste sorted in the Meruelo plant is not available; only the destination of wastes from the selective collection is known. Therefore, greater knowledge about where the recovered fractions go would be of interest for a further study.

There is also the fact that the amount of material recovered after the treatment is considerably lower than the total material present in the remainder fraction, although the treatment efficiencies are not too low. This is due to the inherent inefficiency of the separation process at the Meruelo plant. Thus, although there are materials such as paper or plastic, that are more difficult to recycle due to the number of operations that must follow until their recovery, the amount of recovered materials could be increased by implementing policies that encourage the increase of the selective collection rates. In particular, the source separation of plastics should be specially looked into, since there is a big gap between the 2020 plastic recycling objective and the 2014 plastic recycling rate.

Nevertheless, even if larger source separation rates were implemented, some factors would still hinder the consecution of a circular economic system in the region.

On the one hand, it is not possible to establish a 100% efficient waste recovery system. On the other hand, even if the recovered materials could be sent back to the region, the environmental and economic costs derived from the transport of these materials from the recycling facilities back to the region where they were generated, might make it more attractive to sell the recovered materials nearby the recycling facilities.

As a consequence, although it cannot be stated that a 100% circular economy is viable in Cantabria, efforts can be made to close the material loops to a greater extent.

5. ANNEX I

Table A1: Assumed efficiency for plastic recycling and outlet waste composition in Meruelo.

PLASTICS FRACTION	EFFICIENCY (%)	REFERENCE	COMPOSITION (%)
PET	76	[21]	1,31
PEAD	88	[21]	0,85
FILM	88	[21,26]	8,02
(PU/PVC/PP)	80	[21]	4,46
TOTAL	-	-	14,64

Table A2. Assumed efficiency for Paper, Aluminum, Glass and Iron recycling processes.

WASTES FRACTION	EFFICIENCY %	REFERENCE	COMPOSITION (%)
PAPER	72	[45]	18,9
ALUMINUM	77	[34]	0,67
GLASS	75	[40]	4,35
IRON	91	[37]	2,78

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