HDPE Beverage Closures – Cap2Cap recycling Technological, Legal and Economic Analysis With Focus on EU Market

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Contents

Abstract

Environmental issues and sustainability are getting more and more attention, especially from the younger generation that is caring more about the planet. Large companies are required to react in order to attract this generation as consumers and generate a green image of the company. Moreover, environmental issues got large attention from politics and when it comes to plastics, the plan from the European Union is very clear, they target a circular economy. This study concentrates HDPE beverage caps which we have on every beverage bottle today. The total calculated HDPE cap waste on EU market is 185.000 tons and is mainly down cycled to less demanding application like HDPE pallets. As of today, caps are not recycled in a closed loop, because the European authority for food contact approvals (EFSA) did not give any positive opinion to any technology with the reasoning that not enough scientific data are available. With the most recent legal changes introducing the status of "novel technologies", allowing recyclers to go for commercial production under specific conditions if proof of concept is given. However, the complexity is high starting with the large variation of colours that has been personally mapped within this study in supermarkets in different EU countries. Moreover, the challenge on chemical level in terms of decontamination and material properties is representing a crucial one. HDPE has a structure and physical properties, like the low melting point, that do not allow an efficient decontamination as it would be the case for PET, which is vastly recycled within the EU today. Nevertheless, the strong believe with a quite clean input material coming from a deposit return system can allow fulfilling food contact compliance and the beauty is that this input material is today already available after the sink-float separation of PET and HDPE in existing recycling installations. A big question mark we have still for the safety and performance of a cap that will be produced with a possible rHDPE grade. Based on assumptions how the material properties could change and how these would affect the cap performance, a matrix has been established expressing the complexity for this challenging application, proving that a case by case validation would be required to identify suitability of a rHDPE grade with a specific cap design. Economically, HDPE cap2cap recycling looks very promising even though the initial capex is high it pays off quite fast. We would assume that vertical integration in existing recycling facilities would be favoured due to lower investment and availability of existing input material, which is key in recycling. Considering the energy consumption for HDPE recycling a saving of around 86% savings CO_2 was calculated. Based on the total volume going through today's installed DRS would save emissions of 12.680 cars per year. In a utopian case, that DRS would be installed in all EU countries, a saving of emissions equivalent to 49.950 cars can be achieved. This would clearly contribute to a CO_2 neutrality in future and making our planet greener.

1. Introduction

In the last years, we have a strong movement towards a “greener” world to reduce CO2 emissions caused by humans and consequently reducing global warming. Another important factor is the waste handling and avoiding especially plastic waste, which is not degrading in the environment, remaining in the environment. Pictures like the one shown at the end of the Introduction are very common and are part of the so-called “plastic bashing”. It is often communicated that plastic is evil and is the problem. However, it is not that simple, because plastic is part of our life and cannot be removed easily. Not the plastic itself is bad, but the way people are treating it after usage. If we do not give value to the plastic waste, it will land in the environment. The best proof is the introduction of a deposit return system (DRS) for beverages filled in PET bottles in European countries like Germany and Netherlands, where the collection rate is very high compared to countries where no such system is applied. What is collected, consequently cannot be littered by the consumer and gets higher value by being recycled.

There is a large field of different plastic materials available for different applications, whereas food contact materials are the most challenging ones because they can endanger human health. The ideal case is recycling in a closed loop, which means we want to use plastics for the same application where they originate. Since every material has different properties and functionalities, an analysis of the complete loop is required including supply chain, specific plastics requirements and usage of a suitable recycling process to re-use that plastic again for the same application. Even though research on possible decontamination technologies have been executed already, but an analysis of the complete loop including raw material quality and sourcing and possible effect on the end product is often pending, same as in the specific application in this thesis.

As of today, some research has been executed towards HDPE food contact recycling. The best known example is the recycling of HDPE milk bottles, which has been already introduced in some markets for closed-loop recycling. The analytical and test work concluded that HDPE milk bottles containing up to 100% recyclate from the super-clean recycling process tested and validated during this project can be used safely for direct food contact applications (Welle, 2005). This means having the right application and the right input, HDPE food contact closed loop recycling is possible. For HDPE beverage caps such research have not been done yet, thus I will focus in this work on that application, considering closed loop recycling.

After explanation of HDPE and caps, the legal situation around HDPE caps recycling will be analysed. Furthermore, it will be laid down if technically the recycling is safe and if it is economically viable, because we need to create interest for companies to invest into certain technologies. At the end, the effect of cap performance will be tested using recycled HDPE to ensure safety and convenience for the consumer. Following are the research questions that will be addressed:

1. What is the legal situation of HDPE cap2cap recycling?
2. What are the technically the challenges and how can these be overcome?
3. Is HDPE cap2cap recycling profitable?
4. What influence on the cap performance would a possible rHDPE grade have?

Figure 1: Waste in environment (Mooney, 2014)

To establish the base knowledge about the raw material, product and application, in the next section, we describe the basics of HDPE and caps production including their main features. The next section presents an analysis of the currently technologies available we describe the importance of recycling HDPE in closed loop and the plans of the European Union on plastic packaging. In section four we summarize the most important directives and regulations from the European Union including their interpretation and application to our specific case of HDPE cap2cap recycling. In section 5 the technical challenges are laid down and a specific solution to it with the planned installation Morssinkhof Sustainable Plastics. Afterwards, based on brand owners' specifications the possible risks for the consumer are with a rHDPE grade are analysed. In section 8, we will try to calculate the CO2 impact of HDPE recycling. The manuscript ends with the conclusion.

2. Basics of HDPE and caps

2.1 Manufacturing of HDPE

HDPE is a thermoplastic polymer, featuring high strength-to-density ratio with density between 930 – 970 kg/m³. It is resistant to many solvents. HDPE is used for many applications like crates, fibres, bottles and caps produced by moulding or extrusion.

HDPE is crude oil based; the production chain is illustrated below.

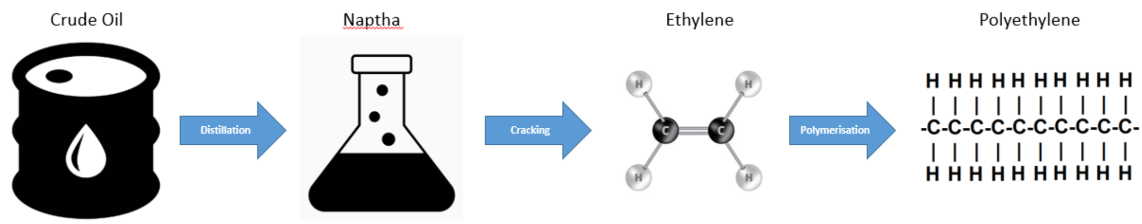

Figure 2: Production process Polyethylene

1. <u>Fractional Distillation of Crude Oil</u>

In the first step, the fractional distillation of crude oil is performed to produce Naphtha. Crude oil is heated to 400°C to ensure that all hydrocarbons are vaporised in the crude oil mixture. Afterwards the crude oil vapour is in the base of the fractionating tower and starts to rise in the column. At different levels, the hydrocarbons will condense if a temperature below the boiling point is reached. Molecules with longer hydrocarbon molecules will condense in the bottom. The shorter the carbon chain, the higher it will rise in the column. Naphtha will typically condense at temperatures between 60°C – 180°C. (secondaryscience4all, 2014)

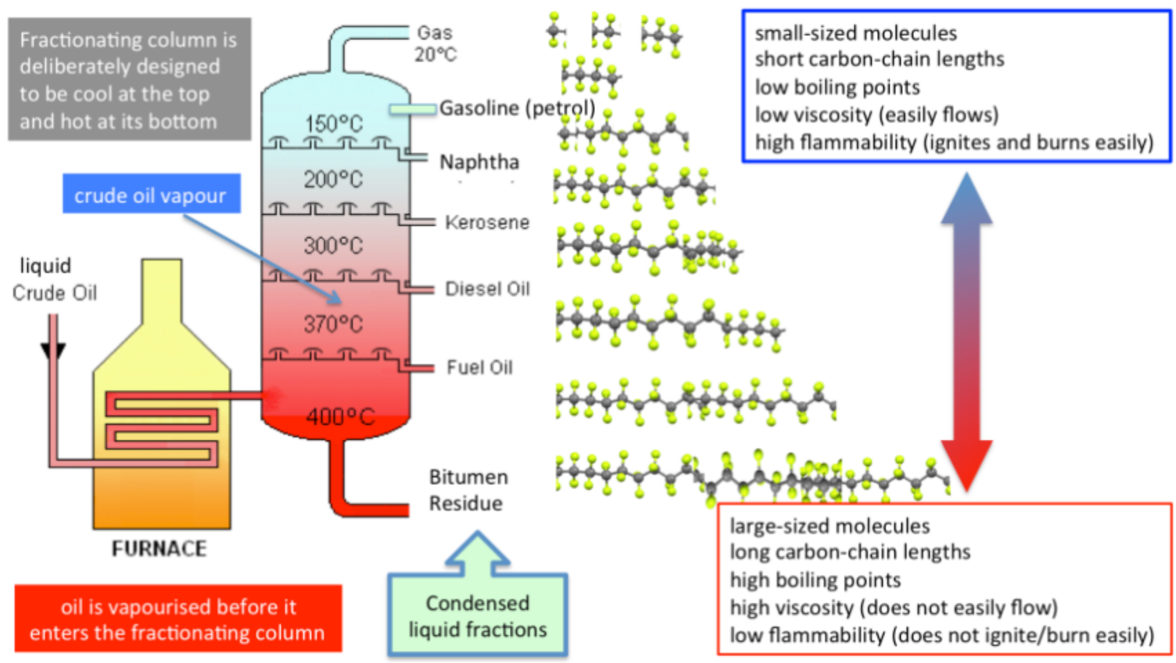

Figure 3: Crude Oil Distillation

2. Cracking of Naphtha

In the second step, Napthta is cracked from longer carbonhydrogen chains into smaller chains by utilizing temperature and steam, thus this operation is also called steam cracking. Naptha is heated up to 550-600°C in the convection zone, where 180-200°C process steam is added. Steam is required to achieve a a lower pressure, reduce risk of polymerisation due to the volume occupied and has a cooling effect in the convection zone. In the furnace the mixture is heated up to 805-850°C and the carbonhydrogens are cracked to smaller chains. Afterwards the high-temperature cracked gas is cooled down in the quenching unit and compressed in the compression unit and dried right after. The last step is the fractionation column where the gas is condensed at multiple levels with Ehtylene right below hydrogen. (Souad Lousdad, n.d)

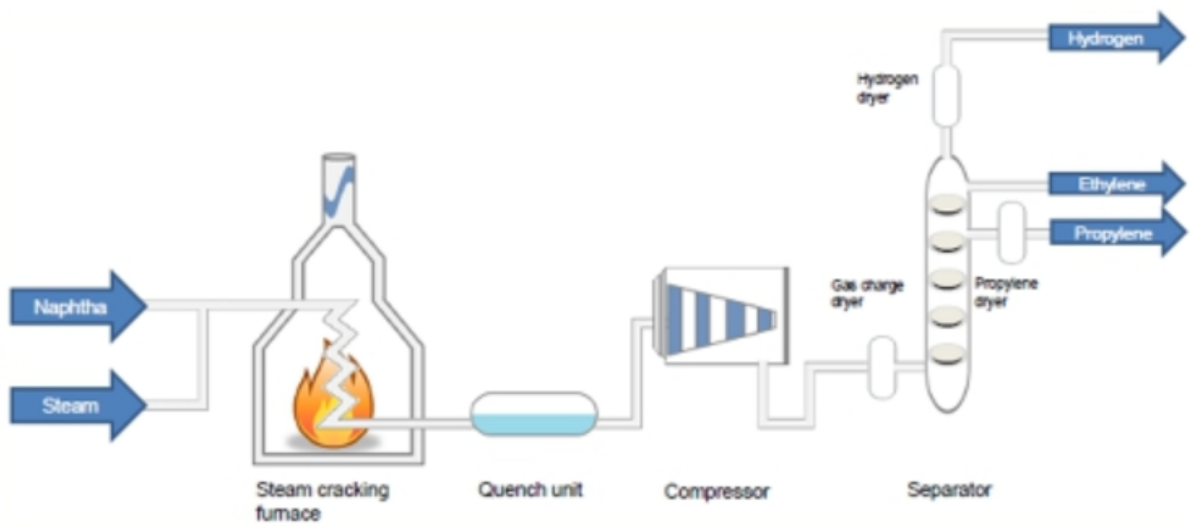

Figure 4: Naphtha Cracking

3. Polymerisation of Ethylene

Ethylene is a stable molecule with four hydrogen and two carbon atoms with a double bond. Polyethylene (PE) is created by the reaction of many Ethylene molecules, where the double bond is broken and the carbons connect into a chain as per figure below. High Density Polyethylene (HDPE) is manufactured by introducing catalysts to avoid branching and achieving high molecular weight of the Polyethylene with high tensile strength and highly resistant to many chemicals.

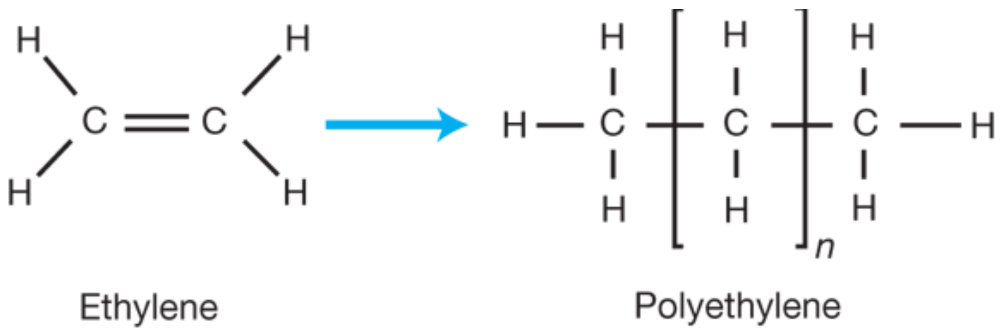

Figure 5: Ethylene Polymerisation (Sharpe, 2015)

The basic principle to produce HDPE is shown in figure 6 that is describing the Ziegler process. In the beginning, an organometallic compound like titanium tetrachloride ($TiCl_4$) is reacting with a metal alkyl aluminium triethyl ($C_6H_{15}Al$) at temperatures 100-130°C at atmospheric pressure. Ethylene is introduced to the reactor with a solvent like hydrocarbon to dissipate heat. The solvent is not allowed to vaporize or react with the introduced compounds. Ethylene is reacting with the active side of the catalysts and polymerisation is taking place, so Polyethylene is created in a solid phase (this process is called slurry polymerisation). The solution is moving into a second vessel where the catalyst is deactivated with alcohol and residual catalyst that was not used during the polymerisation is removed from the solution. In the last steps the solvent is removed, Polyethylene is filtered, dried and extruded to powder or pellets. A molecular weight between 20,000 and 1.5 million can be achieved with the Ziegler process. Following variables are providing freedom to control molecular weight:

- pressure of the reactor vessel (higher pressure, less branches)
- temperature of catalyst (higher temperature neutralizes catalysts)
- ratio of Al/Ti catalyst

(University of Buffalo, n.d)

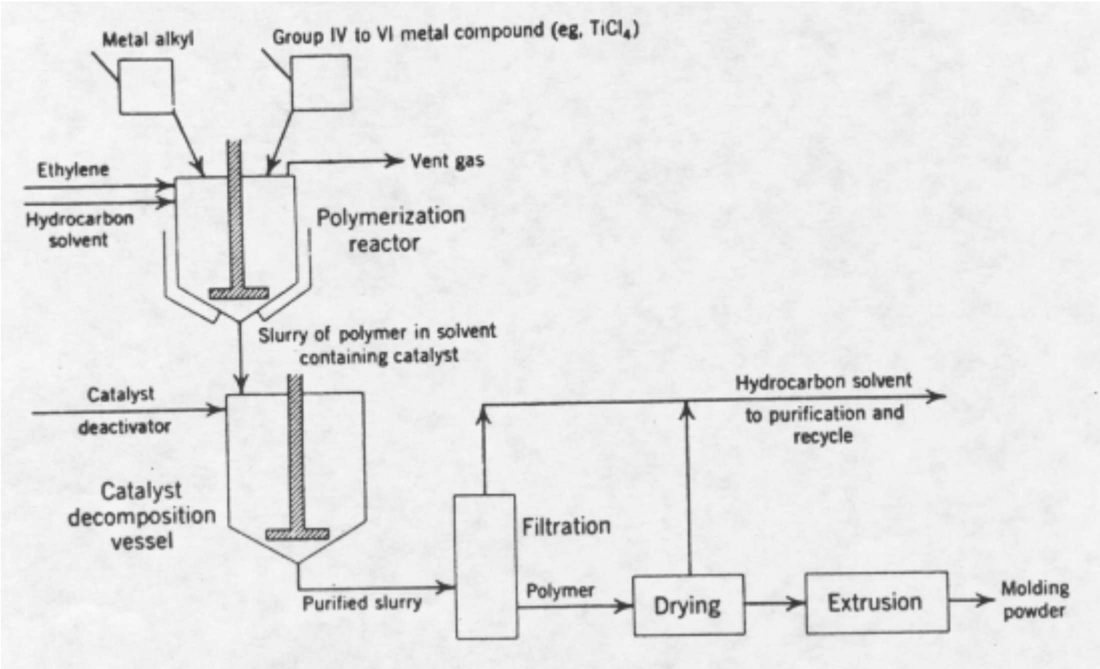

Figure 6: Ziegler Process

2.2 Types of HDPE

The previously introduced Ziegler process is considering a continuous stirred-tank reactor (CSTR). Growing the molecular chain in one reactor gives usually a certain distribution like the one shown on the graph below – a unimodal material. The disadvantage of such a HDPE is that a certain balance between key performance indicators like mechanical strength and processability is required.

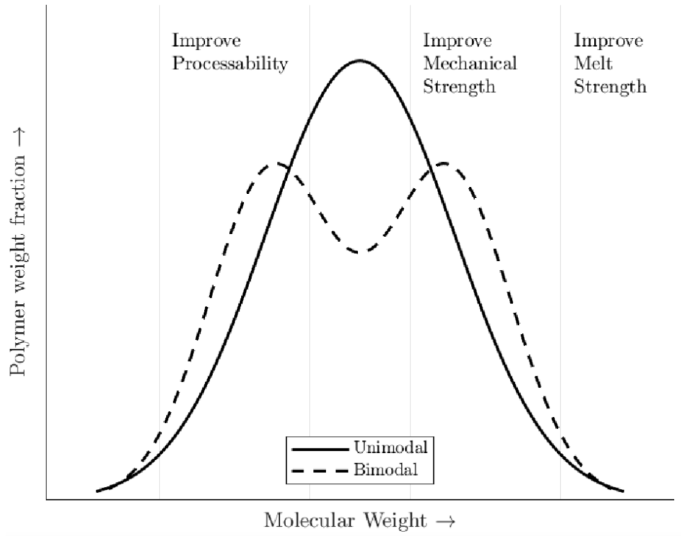

Figure 7: Monomodal/Bimodal (Caceres&Antonio, 2015)

Novel HDPE grades are named bimodal, which are combining advantages of lower and higher molecular weight. This is achieved with newer production processes utilizing two reactors. After the first polymerisation of ethylene in the first reactor, the solution is moved to a second reactor and the molecular weight of the previous solution will grow further, whereas the fresh introduced ethylene will have a shorter chain, achieving the result of a wider distribution of molecular weight.

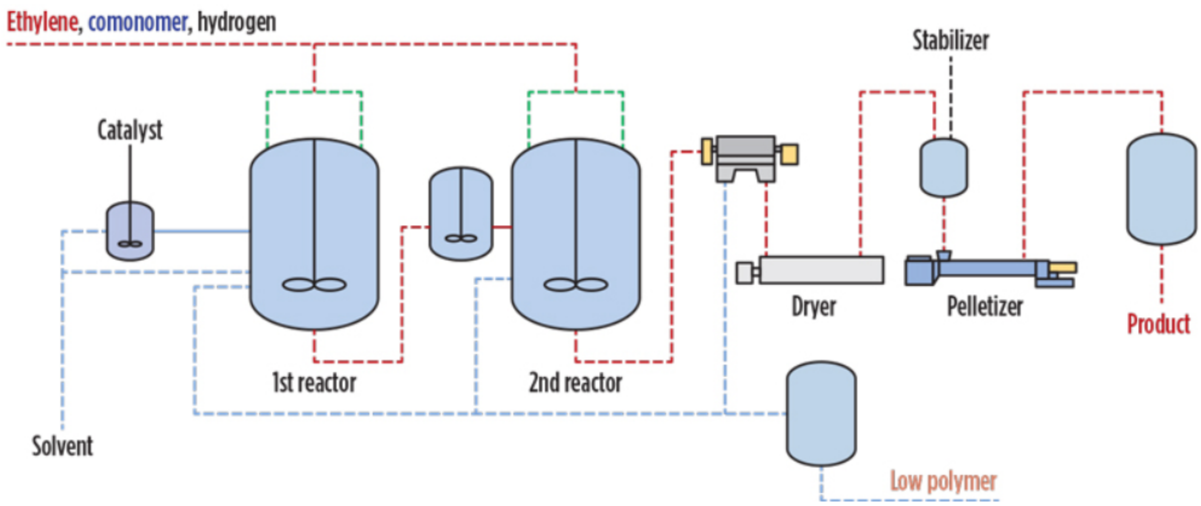

Figure 8: Bimodal HDPE Production (Divey, 2021)

The trend on the market is clearly going towards bimodal HDPE grades, especially because they allow further light weighting due to higher rigidity and better environmental stress crack resistance, but still behaving well during processing.

2.3 What is a Cap?

The first closures invented were metal closures with a crown shaped flange and a natural cork liner for sealing. From there it moved towards aluminium closures with a liner and an inserted tamper evident band. The first "single piece closures" made of HDPE were produced in the 80's by Obrist in Switzerland for returnable glass bottles. These designs were continuously adapted to meet the market needs of changing packaging – e.g. moving from returnable glass over returnable PET packages and finally arriving at today's most common packaging for beverages: non-returnable PET bottles utilizing HDPE closures.

2.3.1 Manufacturing of caps

On the EU market majority of the closures are produced with the injection moulding process. HDPE in the form of granules is put into a small hopper and fed into the heated extruder. A motorised screw pushes the material forwards, due to the shear and compression created the material is melted and transported towards the nozzle of the machine. The melt is injected via a hot runner into the mold and after a certain cooling time the mould is opening and ejecting the closures and the process re-starts. The melt temperature of HDPE is in the range of 130°C and must be processed below 250°C to keep good organoleptic properties.

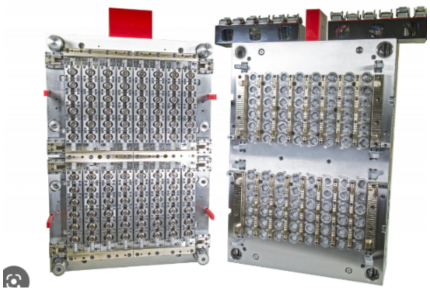

Figure 9: Closure Mold, Courtesy of Corvaglia

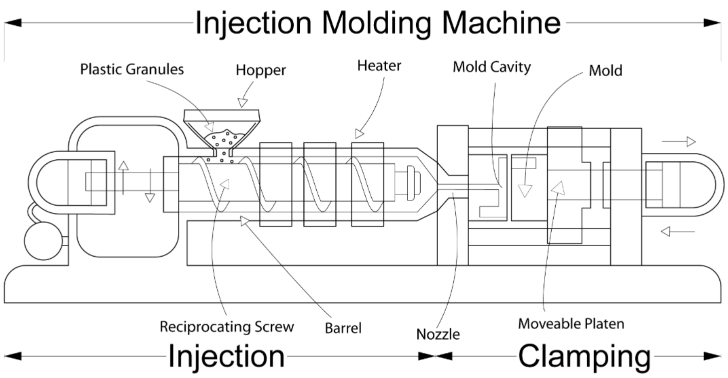

Figure 10: Injection Molding

2.3.2 Caps and their main features

Majority of the closures on the market are threaded, allowing consumers to open and reclose the beverage bottle easily. A cap has to prevent leakage of the product and protect from possible environmental contamination. Closures for carbonated soft drinks (CSD) have to work at higher internal bottle pressures, whereas sensitive products like juices need to be protected from microbiological contamination by undergoing sterilization, which is increasing the technical requirements for closures. Moreover, all closures must have a temper evident function to prove to the consumer that the beverage bottle has not been opened after filling to guarantee that the beverage has not been contaminated (e.g. putting poison inside). To seal the closure on the bottleneck, a sealing package is required that is different depending on the application. The most common are with a single seal that consists only of a plug seal utilized for flat-water applications, which is sealing only on the inner bore diameter of the bottleneck. For applications with higher requirements a double seal is applied, featuring a plug seal and an outer seal that has the advantage of keeping higher pressures of CSD applications and increasing security for sensitive beverages for contamination.

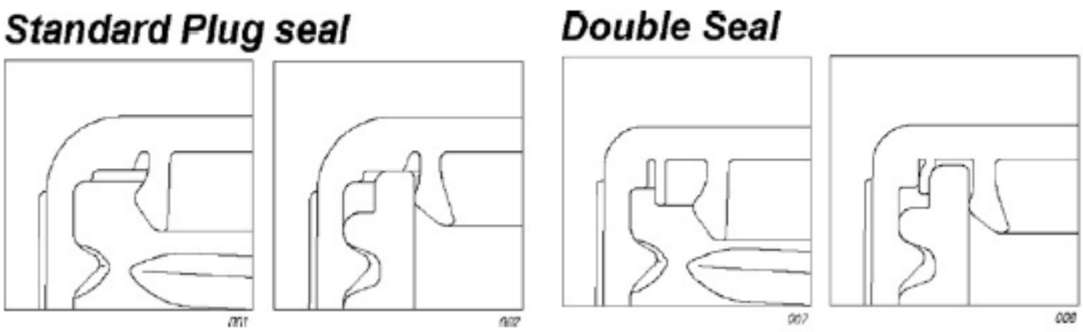

Figure 11: Sealing Designs

It is important to mention that depending on the application, different requirements are set-up for the caps and different HDPE grades are used to fulfil these. Below short summary of the most common closure types on the EU market:

	PCO1881	**38mm**	**29/25**	**26/22**
				
Weight (g)	1,8 - 2,4	2,6 - 3,8	1,1 - 1,5	1,5-1,9
Application	CSD, Water, Juice	Juice	Flat Water	CSD, Water, Juice
MFI	0,9 - 2,5	6,0 - 20,0	6,0 - 20,0	0,9 - 2,5

Figure 12: Most common Closures in EU

Depending on the application, HDPE needs to have different properties that is indicated by the melt flow index (MFI), which is in majority of the cases proportional to the average molecular weight. Moreover, typical HDPE cap grades provide food safety approval and excellent organoleptic properties.

3. HDPE Cap2Cap Recycling Market

3.1 Why should closures be recycled?

Within the EU 2.5 billion tonnes if waste are produced per year, thus legislation is being updated to reduce that amount in order to move into a concept named „circular economy“. This means going away from a linear economic model where products are becoming waste at the end of their lifetime and materials are moving to incineration. Instead, materials should be re-used again, to create as many times as possible in order to reduce waste to a minimum. Figure 13 is describing the process pretty well.

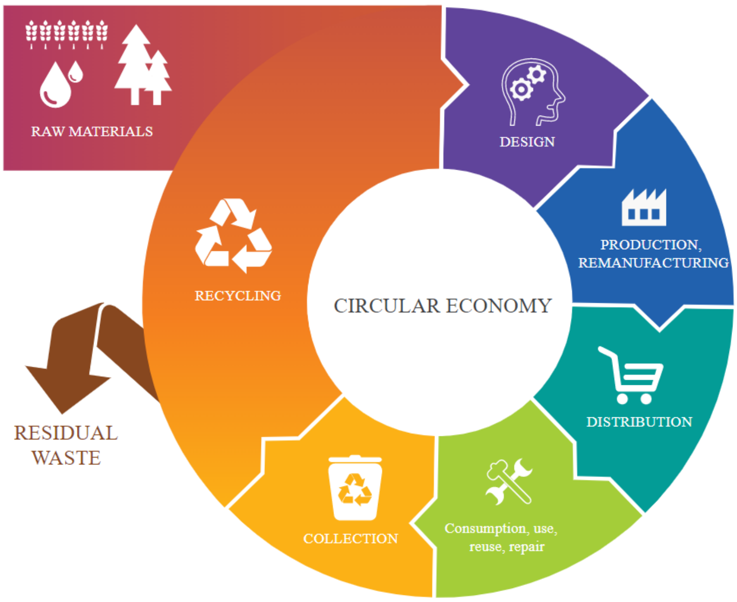

Figure 13: Circular Economy (EU Parliament, 2023)

For the first introduction of a product, raw materials are coming from our planet that is in our case of closures crude oil. Products should have proper design to be recyclable and manufacturing must be set-up in order to process recycled materials. Products are distributed and where possible being reused (not applicable for beverage closures). Product should be collected and recycled to be put back into the cycle. Of course, not all can be recycled and certain residual waste is always present.

The circular economy model is creating many values:

- Reduction of energy consumption (recycling a raw material is requiring typically less energy than producing a new one)
- Reduction of greenhouse gas emissions, because HDPE is fossil based product and in case of reduction CO2 emissions are dropping
- Stimulating economy and creates additional jobs
- Reduction of waste that is going to incineration or landfill
- Encapsulating prices from crude oil prices and creating own feedstock
- Higher independency for HDPE raw material from other countries

3.2 Current Model vs Desired Model

As of today caps are not recycled back into caps, but downscaled to applications that do not require to be food contact compliant, nor they are technically so much challenging that they require special HDPE grade and properties. One of such applications is plastic pallets.

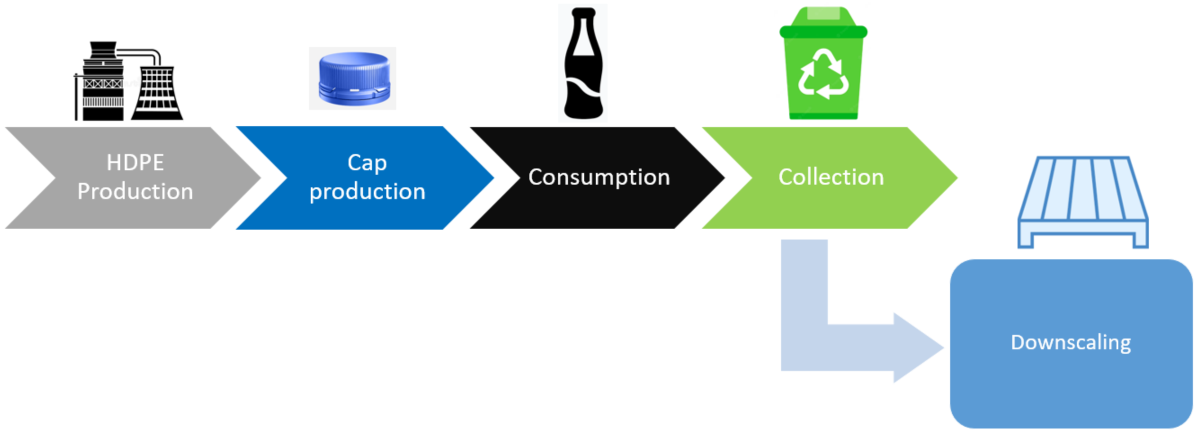

Figure 14: Current Model

In the future, we want to avoid that downscaling of the material, but transition towards a more circular model that allows using the same material back into closures.

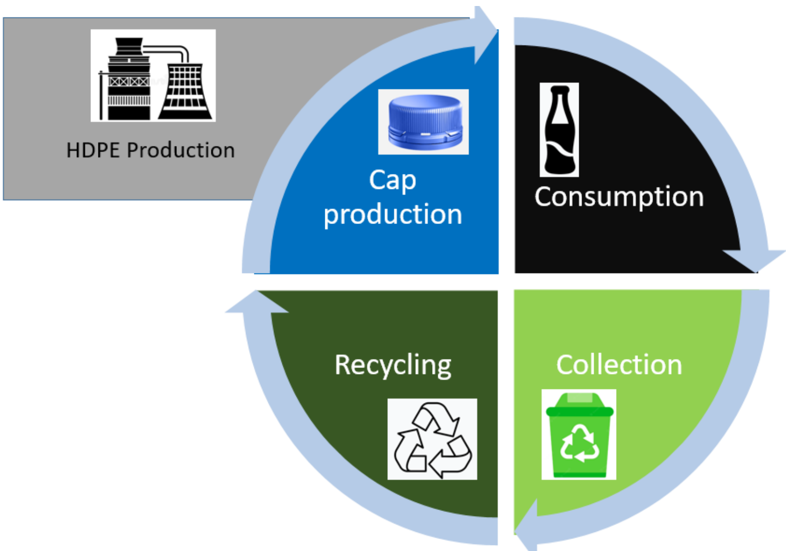

Figure 15: Desired Model

Surely, we will not be able to be dependent only on recycled material, because not all material can be collected and some littering is still occurring. Moreover, during the recycling process a yield leads to a loss in the circle. Furthermore, demographic changes are leading to a higher consumption overall, that cannot be covered with recycling always the same amount.

3.3 HDPE caps waste amount

It is quite difficult to gather data of how much of HDPE is used for HDPE beverage closures, because the HDPE producers do not always have a clear understanding of the final application a converter is running. Is it either a speciality closure, beverage closure or any other injected part. Since no direct data could be obtained on the total consumption of HDPE for beverage closures in the EU, an estimation is made based on following assumptions:

- 70% of the market on PCO1881 at average weight of 2.0g
- 15% of the market on 38mm at average weight of 3.2g
- 5% of the market on 29/25 at average weight 1.3g

- 10% of the market on 26/22 at average weight of 1.7g

Based on these assumptions we utilize following formula:

$$Avg\ weight = (0.7\ x\ 2.0g) + (0.15\ x\ 3.2g) + (0.05\ x\ 1.3g) + (0.1\ x\ 1.7g)$$

Arriving at a final average single closure weight of 2.115g.

Data extracted from Euromonitor below are showing the total consumption of beverage closures (applications: bottled water, carbonates, concentrates, RTD coffee, RTD tea, sports drinks, speciality drinks, juice) for the corresponding years.

Year	2022	2023	2024	2025	2026
Quantity (Millions)	87.321,5	88.841,8	90.428,3	92.032,7	93.682,8

Source: Euromonitor, 2023

To get a proper estimation of the total mass of HDPE consumed for beverage caps we multiply the quantity with the average closure weight of 2.115g and receive following consumption and forecast:

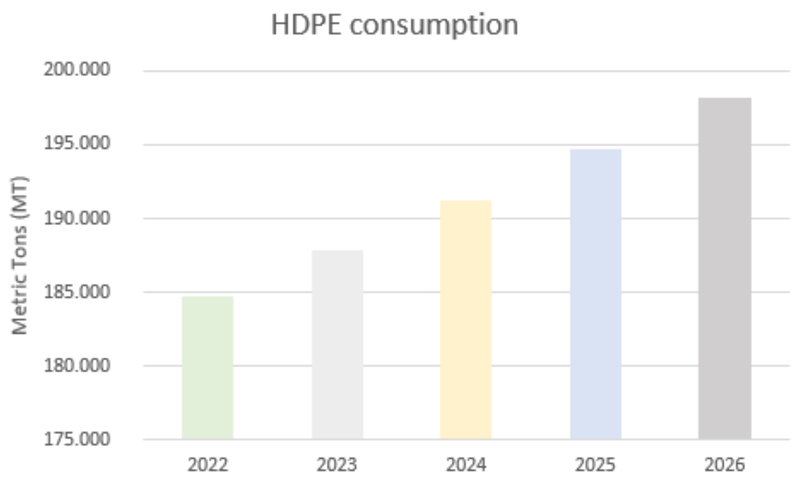

Figure 16: HDPE caps consumption in weight

In 2022, the consumption was close to 185.000 MT, which means that we have a total market of that size to be recycled, provided that all material is collected and can be recycled. We also see that the market is foreseeing to grow by 7.28% until 2026 to a consumption of 198.000 MT.

Figure 17: Tethered Cap (Courtesy of Corvaglia)

Even though bottles are collected, there is a high risk that closures will be disposed separately from the bottles. To increase the collection rate for HDPE closures and avoid littering of the caps, the EU released the directive 2019/904 on Single Use Plastic (SUP), which is saying that all single used plastic should have a closure that should stay on the bottle – the so called "tethered caps". The implementation is programmed for July 2024, meaning products without a tethered cap will not be allowed to be put on the market without such a feature. Surely, this change will increase the availability of HDPE for recycling.

3.4 References for HDPE food contact compliant recycling

As of today, there are no references for food contact compliant in the EU available, but there is one reference for the United States and one application for shampoo in Germany, which are utilizing today the same process. Austrian company “Erema” has developed a specialised line that allows this kind of recycling, but there are differences in the application to EU food contact compliant material that require a positive EFSA (European Food Safety Association) opinion.

1. Envision Plastics from the United States with their grade EcoPrime™

This rHDPE grade is produced by kerbside-collected HDPE bottles, predominantly from dairy products. Envision has obtained a letter of No-Objection from the FDA (Food and Drug Administration) for use in rigid and flexible packaging. (EnvisionPlastics, 2019) However, the requirements from the EFSA are stricter than the ones from the FDA (see chapter 3.3.1). In addition, there are two of challenges to use that grade for beverage caps:

- EcoPrime™ has a quite lot MFI for a resin to be used for injection of caps
- The material is coming mainly from dairy products that are specific in smell and taste, having a big influence on the organoleptic of the rHDPE that can be transferred to beverages, especially in case of flat-water

To overcome these challenges, Corvaglia is mixing EcoPrime™ with another grade at a certain percentage. Therefore, the average MFI of the mix is closer to the usually used virgin HDPE. The organoleptic is improving significantly, because the smell is dissolved with the not smelling virgin HDPE.

Envision Plastics
PCR TECHNICAL DATA SHEET

www.envisionplastics.com

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EcoPrime™

Devolatized Natural Homopolymer High Density Polyethylene
Post Consumer Resin

PROPERTY	METHOD	RANGE	
Melt Index	ASTM D1238	0.55 to 0.85	g/10min
Density	ASTM D792	0.958 to 0.965	g/cm^3
Moisture	ASTM D6980	< 0.050	%
Pellet Size	Pellets/gram	50 to 80	
Volatiles	Gas Chromatograph	<320	ppb
CONTAMINANTS			
0.25 to 1.00mm^2	Specks/10gm	10 max.	
>1.00mm2	Tappi Chart	1 max.	
COLOR			
L*		68.00 min.	
a*	ASTM D6290	-4.50 to 0.00	
b*		0.00 to 13.00	

OTHER PROPERTIES	METHOD	NOMINAL VALUES	
Elongation @ Break	ASTM D638	197	%
Flex Modulus	ASTM D790	111,500	psi
Impact Resistance	ASTM D256	600	J/m
Mold Shrinkage	Length	2.98	%
	Width	2.60	%

PRO B-13-TDS-EcoPrimeTM   Page 1 of 1   15JAN2018 Rev. 8

Figure 18: EcoPrime TDS

2. <u>Shampoo bottle from companies Werner & Mertz and Systec Plastics Eisfeld</u>

The source of this material is coming from the German dual system, referred to as the yellow bag, where practically all packaging obtained from a shop should be disposed of. Cosmetic application like shampoo has also high standards and is often equalized with food contact compliant materials, however in this case the requirements were lower. Nevertheless, a proper decontamination of the collected HDPE was obtained to achieve approval on cosmetic applications. (Erema, 2019)

Both products are using Erema's technologies for recycling with the below described process.

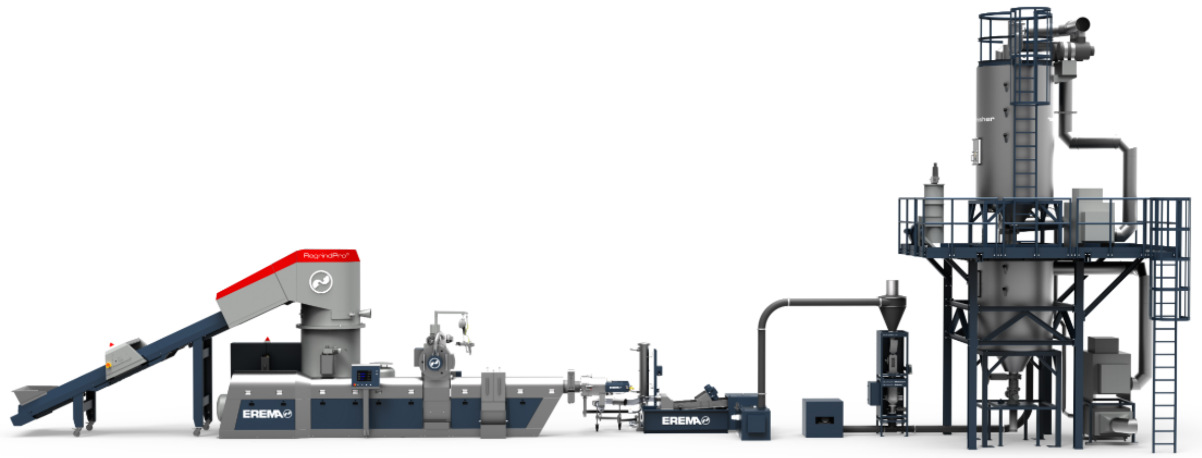


Figure 19: Erema Recycling System (Courtesy of Erema)

The grinded and hot washed HDPE is entering in a preconditioning unit where it is warmed up to a certain temperature and flushed with air for a residence time of one hour. The regrind is entering into a degassing extruder followed by a melt filtration and a unit to granulate the melt. In the last step, the material is sitting for some hours in a so-called refresher, where it is flushed by air at a certain temperature. The temperature must be high enough to allow volatiles to migrate to the surface, but should be lower than the melting temperature to avoid gluing of the pellets. Volatiles are picked up by the flushing air and removed from the hopper, same as the smell is removed with this fresh air improving the organoleptic.

3.3.1 Key differences FDA and EFSA

As described previously, in the United States, food contract materials are regulated by the FDA by Codes of Federal Regulations, policy guidelines and "Generally Recognized as Safe" approvals. However, individual states can release specific measures. In the EU, on the other hand the European Commission has the authority to regulate food contact materials, mainly based on the scientific opinion of the EFSA. Member states are obliged to follow these regulations, but can put additional requirements.

The FDA requests that both, household and food packaging should be hazardless to the consumer, but due to resource limitation is focusing and enforcing primarily only on food packaging. In EU, both are enforced equally.

A big difference is in the compliance assessment, where the US is focusing on the individual material only, whereas the EU on the final product. For many materials, simulations of food contact are performed for the specific food in the EU, but in the US, the same process would apply if the material were the same, even though the actual food would be different. Furthermore, in the US is an option to exempt a specific material testing, if the material is below the threshold of regulation, which is not possible for the EU.

For our specific case, the FDA would analyse only the final product after recycling and give it an approval without digging into the full process and the responsibility would be with the producer to keep the output quality stable. The EFSA would analyse the complete process including analysing source of material to give a positive opinion.

4. Legal Status of HDPE Beverage Closure Recycling

Within the European Union, the "Commission of the European Communities" has the authority to set up regulations and guidelines for materials that come into contact with food. The decisions are made with the support of EFSA, who provides independent scientific advice. Their work involves collecting scientific data including expertise, providing most current scientific advice on food safety problems and communicating these publicly. This involves cooperation with EU countries and all required stakeholders involved.

To get an understanding the legal situation, following regulations from the European Commission are of importance and are being analysed chronically:

- 2002/72/EC: relating to plastic materials and articles intended to come into contact with foodstuffs, dated 6th August 2002
- 1935/2004: on materials and articles intended to come into contact with food and repealing Directives 80/590/EEC and 89/109/EEC, dated 27th October 2004
- 2023/2006: on good manufacturing practice for materials and articles intended to come into contact with food, dated 22nd December 2006
- 282/2008: on recycled plastic materials and articles intended to come into contact with foods and amending Regulation (EC) No 2023/2006, dated 27th March 2008
- 10/2011: on plastic materials and articles intended to come into contact with food, dated 14th January 2011
- 2022/1616: on recycled plastic materials and articles intended to come into contact with foods, and repealing Regulation (EC) No 282/2008, dated 15th September 2022

All regulations released by the Commission have the target to harmonize rules and eliminate differences in laws of the Member States. All members have to follow these regulations; however, they can still apply more strict rules in their sate.

4.1 Directive 2002/72/EC relating to plastic materials for food contact

This directive set-up the basic rules on manufacturing of plastic materials for food contact. The main message is that plastic materials shall not transfer their constituents to food in quantities exceeding 10mg/dm³. On the other hand, limit should be 60 mg/kg for containers between 500ml and 10l, articles that can be filled or not practicable to estimate surface area and caps, gaskets or other sealing parts.

In the Annexes of the directive all materials (monomers) are listed that may be used in the manufacturing of plastic materials. If applicable certain restrictions to these monomers apply, like specific migration limit or maximum permitted quantity of residual substance in the material. (EU Directive 2002/72/EC, 2002)

However, these lists do not include impurities in the substances and therefore no contamination is considered that possibly can occur on plastics after use that will end up in the recycling stream.

4.2 Regulation 1935/2004 materials for food contact

The principle of this regulation is that any material that is coming in contact directly or indirectly with food must be sufficiently inert to preclude substances being transferred to food in quantities large enough to endanger human health or to bring and unacceptable change of the composition or deteriorate its organoleptic properties. (EU Regulation 1935/2004, 2004).

After the establishment of the EFSA and laid down principles and requirements of food law in Regulation 178/2002 of the EU Parliament and Council of 28th January 2002, for the first time procedure has been established on EU level to be followed for food contact materials. To have harmonization across the EU states and their communities, the EFSA will carry out the safety assessments. Differences in national laws are therefore excluded and allow free movement of goods between countries. A risk management decision is done after the safety assessment, on whether the analysed materials should be added on the authorised list of substances.

Traceability of materials should be ensured to allow recall of defective products from the market; furthermore, declaration of conformity should be issued confirming that the material complies with applicable rules.

Recycled materials are only mentioned to the level that they should be added for environmental reasons. Strict requirements should be applied to ensure food safety and consumer protection. However, it is recognized that national laws and provisions are lacking in this regard and it is clearly understood that specific measures for recycled plastic material should be established and the regulation is saying that a draft of specific measures should be made available to clarify the legal situation. The same rules that apply for virgin materials, apply also on recycled materials in terms of:

- Purity standards
- Specific limits of migration of certain constituents
- Overall limit on migration into or on to food
- Rules concerning sample collection analysis methods to check compliance

Very important is the article 3, because many other regulations are referring to this. It is saying, that materials for food contact should be manufactured under good manufacturing practice, so that under normal conditions of use they do not transfer constituents to food in quantities that:

- endanger human health
- bring unacceptable change of food composition
- deteriorate organoleptic characteristics

For the first time the role of EFSA is formulised: consultancy activities related to food safety that are the basis for liable provisions.

The process to authorise a material for food contact is described:

- application to be submitted to competent authority of the Member State (competent authority to be assigned by the individual Member State)
- it contains a technical dossier based on guidelines provided by EFSA
- within 14 days the acknowledge receipt to be issued
- EFSA should issue an opinion within 6 months after receipt of application, that can be extended by another 6 months, provided that a proper explanation is issued

- Within this period the information and documents that have been submitted are verified and examination on the compliance with safety criteria as per Article 3
- Opinion is forwarded to Commission, Member States and applicant
- In addition the opinion is made public with deletion of confidential data like processing data

Member states are obliged for regular official controls to ensure compliance and where necessary the Commission and EFSA are supporting in developing technical guidance on sampling and testing to assure coordinated approaches. Community reference laboratories should be used for analytical testing to ensure a high quality and uniformity of analytical results.

4.3 Regulation 2023/2006 Good Manufacturing practice for food contact materials

Regulation 2023/2006 lays down rules on good manufacturing practice (GMP) for food contact materials listed in Annex 1 of Regulation 1935/2004; plastic is one of these materials. All stages of the supply chain from manufacturing, processing and distribution of the materials are affected by this regulation.

The definition of GMP as per regulation:
'good manufacturing practice (GMP)' means those aspects of quality assurance which ensure that materials and articles are consistently produced and controlled to ensure conformity with the rules applicable to them and with the quality standards appropriate to their intended use by not endangering human health or causing an unacceptable change in the composition of the food or causing a deterioration in the organoleptic characteristics thereof. (EU Regulation 2023/2006, 2006)

This includes establishing a quality assurance system (organisation and documentation of required specification/quality) and quality control system (measures established to ensure product is within specification). Materials have to show compliance at all stages of production, from income control of starting materials over intermediate controls and on finished materials. Part of the quality control is also monitoring the achievement of GMP and applying countermeasures if any deviations appear. Documentation has to be established and made available to competent authorities in case questions to safety of finished material appear.

4.4 Regulation 282/2008 recycled plastic materials for food contact

This was the first regulation released for recycled plastic materials after consulting with EFSA. Up to here all recycled plastic materials had basically to conform to previous regulations, where same rules apply as on virgin material.

It is necessary to comply with migration limits mentioned under 2002/72/EC, which laid down authorized substances for plastic food contact material production. This has the target to ensure that recycled plastic material is providing the same safety as authorized monomers and additives. In addition, the recycled plastic should not endanger human health, bring unacceptable change of the food or influence the organoleptic as per regulation 1935/2004.

Producers of recycled plastics have to comply with GMP set out under regulation 2023/2006 and it is necessary for them to provide a declaration of conformity to allow traceability between business operators.

It is clearly explained that this regulation applies only to mechanical recycling and not to chemical depolymerisation technologies, where the base to create the recycled plastic is monomers and/or oligomers. These technologies have to comply with 2002/72/EC and are treated like virgin plastic materials. Furthermore it is stated that post industrial production, like offcuts and scraps that has not been in contact with food or contaminated otherwise can be re-melted directly and used for production, thus are also not part of this regulation, same as recycled plastic behind functional barrier.

Plastic waste can be contaminated in different ways, by coming in contact with chemicals due to misuse or even plastic waste originated from food contact approved material can be mixed up with non-food contact grade. Thus, only the combination of the input material, sorting efficiency and effectiveness of the recycling process itself should be evaluated to ensure the safety of recycled plastics. All the different aspects should undergo an individual authorisation, followed by a combined evaluation. It is mentioned that for polyolefines a sorting efficiency of 100% may be necessary, that can be achieved with product loops in a closed and controlled chain, whereas for PET the safety is realistically achievable with kerbside collection system. In a challenge test, a recycling process has to demonstrate efficient reduction of potential contamination and in commercial production, the contamination level has to be checked continuously and be below or on the same level as performed during the challenge test.

To get authorisation for a recycling process a safety assessment has to be performed by the EFAS, followed by a risk management decision. The EFSA shall give their opinion within 6 months after receiving the application. It is to mentioned, that EFSA is issuing only an opinion, but the European Commission is granting or refusing the authorisation. All authorised processes should be part of a public register and to ensure safety over time, the recycling plants are inspected and controlled by the Member State.

4.5 Regulation 10/2011 plastic materials for food contact

Directive 2002/72/EC is supposed to be replaced by this Regulation that is the most current for plastic materials for food contact. The replacement was necessary, because the adoption of approved substances into national law took too long and hindered innovation. In addition, a directive is laying down results that a Member State should achieve, whereas a regulation is a binding legal force for all Member States. Same as Directive 2002/72/EC the Regulation 10/2011 is representing a specific measure of Article 5 of Regulation 1935/2004 to establish rules for plastic materials for their safe use.

The EFSA has to issue a risk assessment for each substance and what changes significantly is that also it should cover also relevant impurities, what was excluded in Directive 2002/72 /EC. These impurities are called non-intentionally added substances (NIAS), which are also present in post-consumer HDPE. Where relevant only the main impurities are considered for the risk assessment.

Furthermore, the different migration methods like specific and overall migration limits are more clearly defined, but not changed in terms of their values. Once a new substance is qualified, it should be added immediately to the regulation in order to allow manufacturers be faster going into production with these. (EU Regulation 10/2011, 2011).

What is very interesting that if a multilayer plastic part is used for food contact, that the layer not in direct contact with the food does not require any approval. This means that producing a multilayer closure could bypass a recycling process, having an outside layer of virgin HDPE and inside layer of simply grinded, hot washed post-consumer HDPE.

4.6 Regulation 2022/1616 Recycled Plastic Materials for Food Contact

Just in September 2022, the most recent regulation on recycled plastic materials for food contact has been released, with the target to specify better requirements and conditions to place recycled plastic materials on the market including their production. For the first time detailed procedures for the development and operations of recycling technologies are being set-up to avoid confusion on several sides.

To get a proper understanding and increasing standardisation, several definitions have been introduced which are explained and visualized in figure 20 based on PET Bottles recycling process.

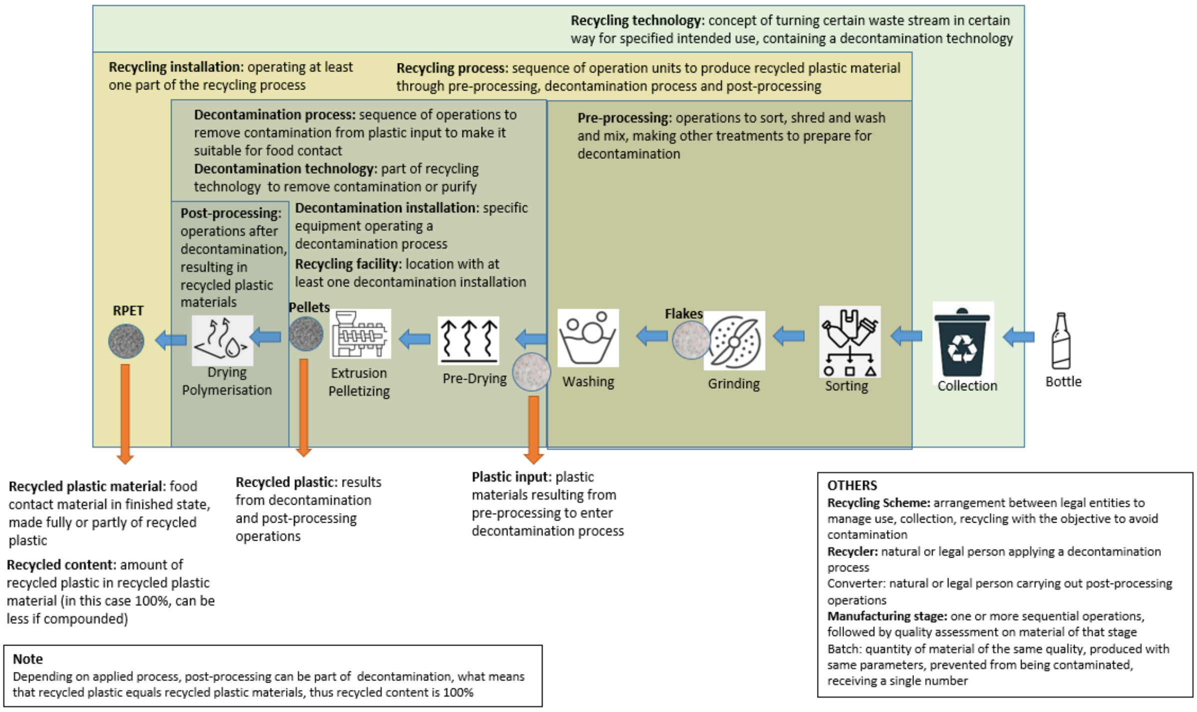


Figure 20: Definitions

Furthermore it is now defined what a suitable recycling technology is. It has to comply with Article 3 of Regulation 1935/2004 to not endanger human health, nor influence organoleptic properties of the food and in addition require being microbiologically safe. More factors are now being considered for the approval of a technology, like collection mode and input material, same as the intended use. Every recycling process requires authorisation, whereas at the introduction of the updated Regulation only mechanical recycling for PET and post-industrial waste in a closed and controlled chain is approved. Any technology without positive opinion yet is considered as a novel technology and any technology that requires a specific input and/or processing parameters will require and individual authorisation.

Plastics that are placed on the market need to comply with migration limits specified in Regulation 10/2011 using suitable or novel technology, which has received individual authorisation where required.

The requirements for every step in the recycling process are clearly defined and are summarized in figure 21.

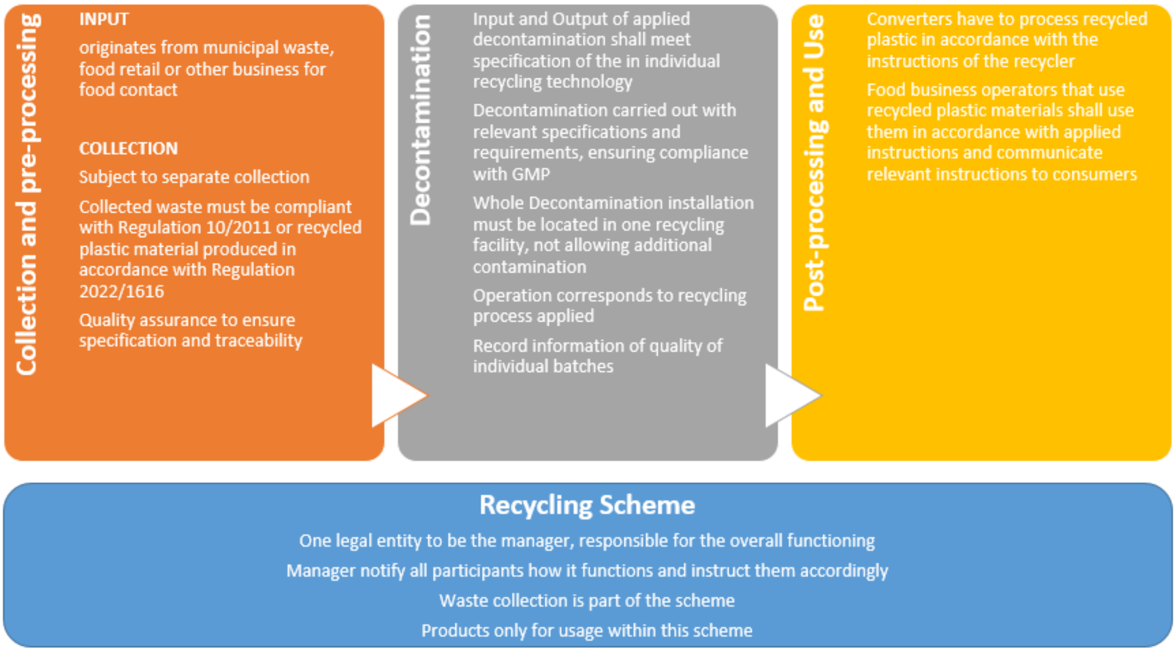


Figure 21: Requirements

Probably the most important part of this Regulation is the introduction of "novel technologies". It is a newly introduced status that a technology can receive, provided that it is conceptually proven that the technology can achieve the required decontamination and guarantee an output that is safe. The process of setting-up a novel technology until moving into "suitable technologies" is described below.

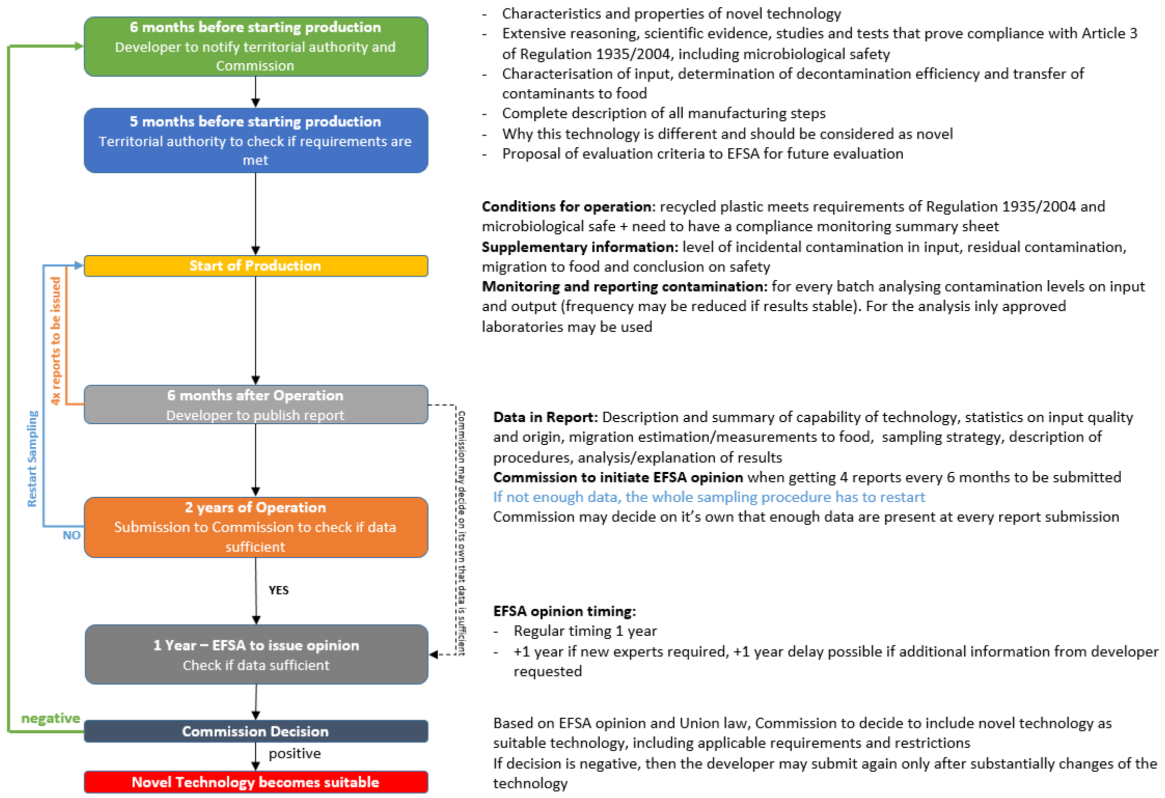


Figure 22: Novel Technology

The Commission decision also contains a decision if individual authorisation is required for every recycling process. This is the case, if the input material needs to be sorted in a certain way and if process parameters might be specific to the required output. Before Regulation 2022/1616 was in place, there was no clear process followed on the authorisation of the individual recycling processes, e.g. all recyclers of PET in Europe were operating without authorisation, because even if they applied for it, it has never been granted. The process is now very clearly laid down in this Regulation, indicating that EFSA has to publish a detailed guidance on the evaluation criteria.

To get authorisation, the developer has to submit the application to a competent authority in the Member State, containing a full technical description including pre-/post-processing, quality parameters and control procedures. Within 14 days, the application has to be accepted and EFSA needs to be informed, who will inform the Member States and the Commission about it. Within 6 months, EFSA has to issue their opinion, which his expandable by another 6 months with reasonable explanation. Based on the opinion and Union law, the Commission will grant the authorisation and where needed specific requirements should be included. The Authorisation is not taking any civil or criminal liability from business operators regarding food safety contact of recycled plastic materials. The recycler has to inform the Commission if any additional information collected during operation might affect the evaluation of authorisation and contrary, the Commission and Member States can on their own initiate re-evaluations.

A Union register for novel technologies, recycling processes/schemes and decontamination installations is being established and made public. Every decontamination installation needs to be registered 30 days before production start, referencing to the authorised recycling process. For each decontamination installation, a compliance monitoring summary sheet has to be established to document and demonstrate compliance with this regulation.

Recyclers and their installations are subject to official controls and audits on following GMP and operation according to compliance monitoring summary sheet. If during the audits non-compliant batches have been found, the recycler has to put measures accordingly to avoid them in future and in worst-case withdrawal of the authorisation can be applied.

4.7 Conclusion on Legal Situation

It is quite evident that the new Regulation 2022/1616 is bringing major changes, providing a structural approach and guidelines for the development of recycling technologies. When it comes to HDPE recycling, up to this regulation there was never a positive opinion in accordance with Regulation 282/2008 issued by the EFSA. EFSA opinions have been analysed that included below comments:

1. "On the other hand, the CEF Panel emphasised that the uncertainties arising from the lack of sufficient scientific knowledge and the consequent conservatism of the selected criteria could allow the conclusion that a process is safe when criteria are met but do not allow a conclusion to be reached on the safety of the processes when the criteria are not met. In such cases, additional data are needed." (EFSA Journal 2015;13(2):4016, 2015)

2. "The CEF Panel recommended to acquire more knowledge on the possible contaminants sorbed into post-consumer HDPE articles used as input and covering potential polar and non-polar contaminants with molecular weights up to 1,000 Da (g)". (EFSA Journal 2022;20(1):7001, 2021)

To make it clear, the main message is that not enough data are available in terms of decontamination efficiency, nor in terms of possible contaminations in input plastic to take a clear opinion. Thus, the EFSA was issuing a negative opinion, even at some conditions of the input plastic a certain recycling technology might have been viable. With the new regulation, exactly this point is addressed. As long as there is enough scientific evidence and some decontamination trials were carried out, proving that the output is will not endanger human health and is microbiologically safe, the green light is given to start a production and collection of data can be carried out in real production environment (novel technology). Surely, more strict requirements apply in regards to quality assurance, but this gives the opportunity to collect enough data and not give to the EFSA the opportunity to opt for a negative opinion due to lack of available data. Since every batch needs to be checked for quality compliance, the risk for the consumer is very low to not existing and there is no reason not to release that batch to the market.

To conclude, the new regulation will enhance innovation on the market and accelerate the transition towards a circular economy in the European Union.

5. Technical Challenges and Solutions

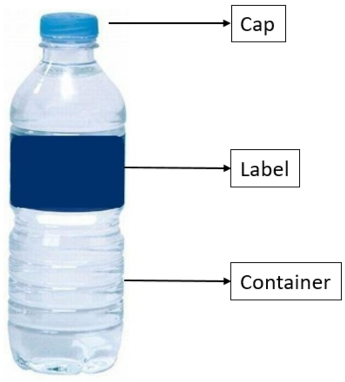


Figure 23: PET Bottle

The complexity of recycling beverage caps is very high, thus first the basics will be laid down explaining the complexity. A plastic beverage bottle is consisting of several components. The container itself that is made our of PET, the cap made out of HDPE and the label that can be made out of several materials like paper, polypropylene, polyester or vinyl. For this work the process of collecting the whole bottle of container, cap and label will be considered, so without any consideration of littering of individual components.

5.1 Collection

The first step is the collection of bottles after usage that can be managed in different ways:

1. Collection with other waste

Also referred as the kerbside collection, the waste is collected directly at households. Different variants existing here, from having all waste together over separating recyclable waste like plastic, metal and glass from other waste to having a separate collection for plastics only. The big advantage of separating more lies in the lower contamination, especially microbiologically cleanness. Moreover further sorting is eased if biologically degradable products are separated that can easily cause sticking of different packages to each other.

	All in one	**Recyclables separately**	**Separate collection**
			
Description	All waste is put together in one bin.	Recyclable products are separated from other waste.	All waste types are collected separately
Disadvantage	• bio-waste is collected with all other waste, that is creating big challenge for microbiological cleanness • Highest contamination risk • Sticking of materials to each other possible that is making it more difficult to separate later	• Beverage bottles are collected with all kind of recyclable material like paper or plastic bags, that is making further separation more complex	• All kind of plastics are collected together, despite the origin. • Non-food applications like detergent are bringing high risk of contamination of the food packaging and increasing the performance requirements for the decontamination unit

Figure 24: Kerbside Collection

2. Collection Points


Figure 25: Collection Point (Skiphtelinebarcelona, 2019)

Collection points allow the consumer to bring their waste to a certain place where waste is separated. It has the advantage that not all sorting has to happen at households, what is making the logistics much easier. Figure 24 is showing such a collection point from Barcelona, where plastics are collected separately. However, this system has the same weakness like the separate collection at households to not have proper control what is really thrown in the bin by the consumer. In addition, all plastics are collected, so no separation by material is happening, nor any distinguish between food and non-food packaging.

3. Deposit Refund System (DRS)

The most powerful tool to collect bottles is the DRS. When buying the bottle, the consumer is paying a deposit for the packaging (e.g. in Germany 25 Euro Cents). After consumption, the package is brought back to the supermarket, where reversed vending machines (RVM) are located. The RVM is issuing a ticket accordingly, which is representing the credit for next purchase in the supermarket. The system can be applied only for PET bottles, but also for other packaging materials like glass and metal cans. The different packaging materials can be separated by the RVM. PET bottles are then compressed and packed as bales before moving to the waste centres. The big advantage is that PET bottles are separated from any other waste stream and since only beverage products as of today need to be returned, it can be assured that returned products are originated from food applications, thus input material is compliant with Regulation 10/2011.

The DRS is implemented in couple of EU countries and many other countries are in the implementation phase or at least discussing a possible establishment.

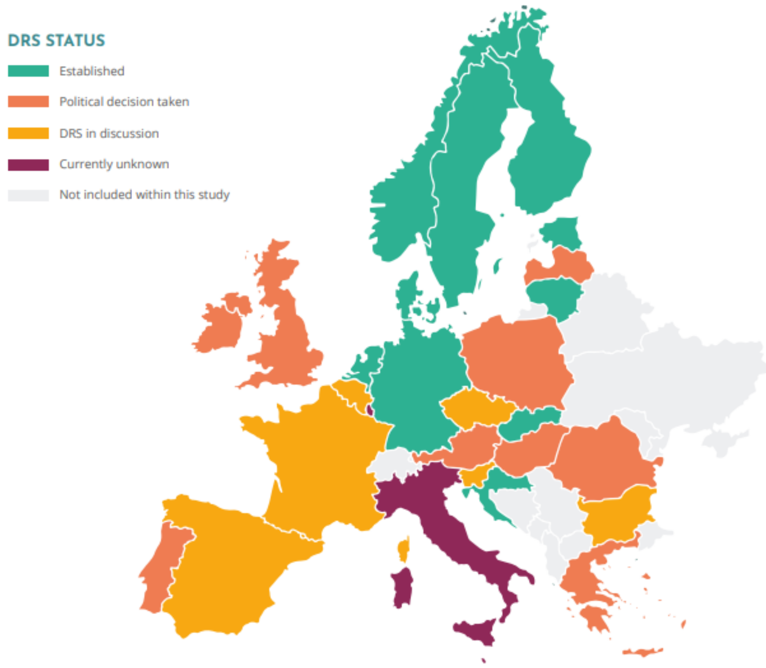


Figure 26: Status of DRS in EU (Eunomia, 2022)

By giving the packaging even after usage a value, the consumer is motivated to return the packaging and this is clearly increasing collection rates compared to other systems. Figure 27 is pointing out that countries in Scandinavia and Germany, who implemented successfully the DRS are achieving by far higher collection rates than other countries. All what is collected cannot be littered and end up in our oceans and increasing clearly the sustainable character of plastics.

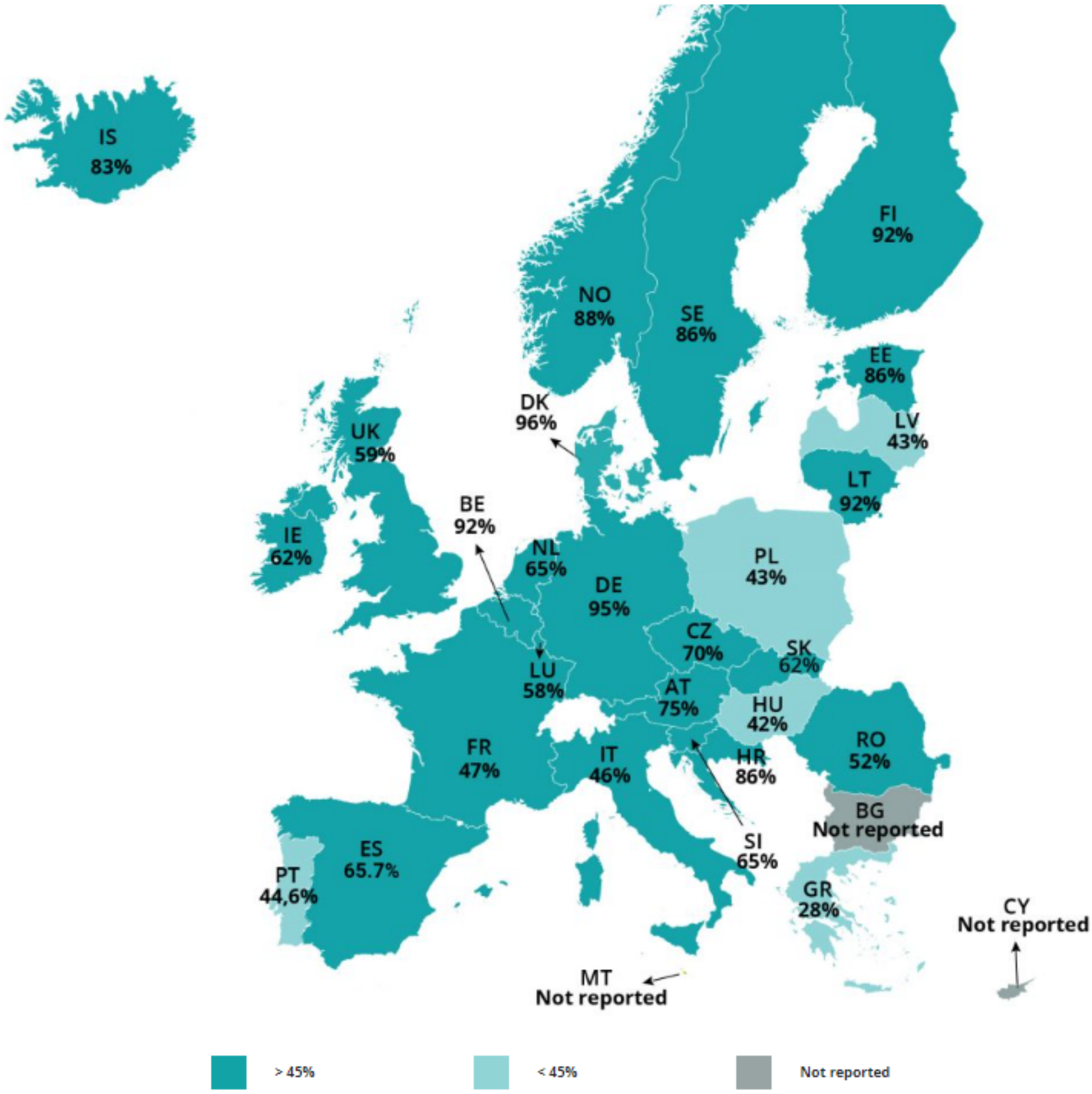


Figure 27: Collection Rates in EU

We can conclude there are several possibilities to collect the HDPE caps, whereas the DRS is the most effective one.

5.2 Waste Sorting

Collected waste is delivered to Material Recovery Facilities (MRF), where it is being sorted by grades and prepared for dispatch to further processing. Figure 27 is showing a typical design of a MRF.

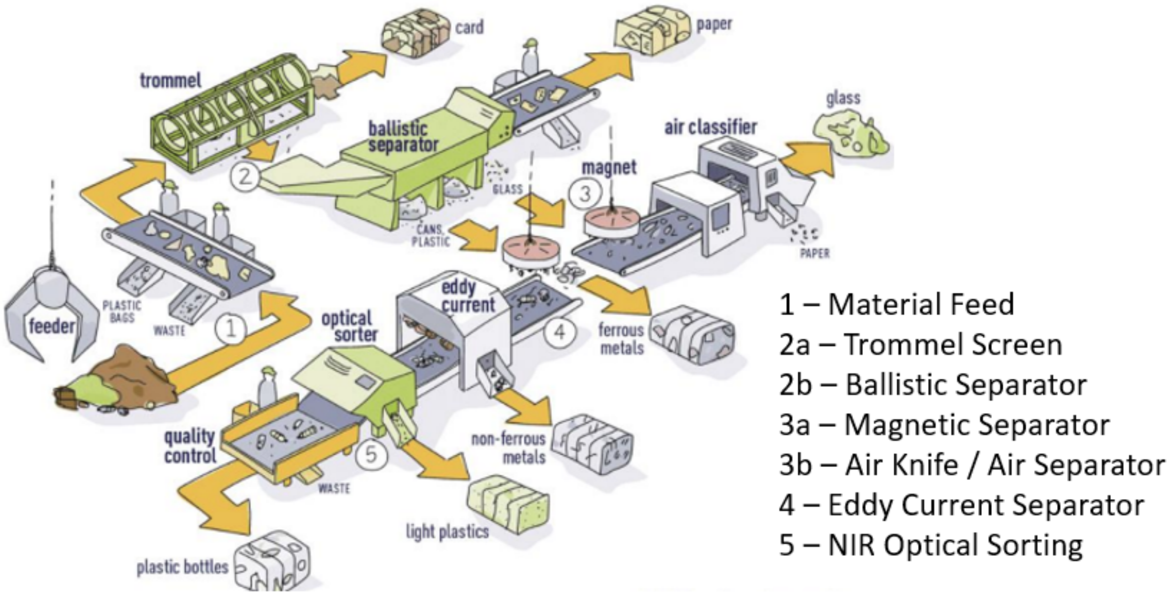


Figure 28: MRF (WikiWaste, 2022)

Waste is delivered to the facility and fed into the Sorting system. Majority of waste is delivered in a bag and a Bag Breaker is opening the bags with blades on counter-rotating drums. Plastic bags and waste is sorted by hand out. In the next step in a Trommel Screen the separation of larger, lighter mixed paper and cardboard from other materials is happening. These other materials are the fed into a ballistic separator, where paddles on an inclination are pushing light and flexible material up and heavy materials fall downwards. The paddles have small holes, so finer material can fall through these. Depending on the speed and incline angle, different materials can be sorted like paper, glass, cans and plastics. The plastic material is then going through a magnetic separator, where ferrous materials can be filtered out. In the case of further glass sorting an Air Separator is used to filter fine papers out. In an Eddy Current Separator non-ferrous metals are filtered out with the support of a magnetic rotor that contains alternating poles. When a piece of non-ferrous metal passes over the magnetic rotor, the magnets inside the shell rotate past the metal at high speed which forms eddy currents to create a magnetic field around the piece of metal. The polarity of that magnetic field is the same as the rotating magnet, causing the non-ferrous metal to be repelled away from the magnet. (WikiWaste, 2021)
At this stage, we have plastic materials left and can sort by use of a Near-Infra-Red (NIR) Optical Sorting by materials. The basic principle is measuring the wavelength of the light that bounces off an object and separating consequently with an air knife. Materials may be sorted by a series of such units. Various polymer types can be sorted and even PET bottles by colours. The output ultimately are bales of PET bottles. Here we can see directly the big advantage of a DRS, which would avoid this sorting and PET bottle bales would be shipped directly to further processing at Plastics Recycling facilities.

5.3 Separation from Bottle

Figure 29 is showing a typical PET bottles recycling line that are located at Plastics Recycling facilities.

Figure 29: PET Bottles to Flakes Process (Sorema, 2023)

Bales of bottles are fed on a conveyor into the system and a broken by a bale breaker with use of paddles that are installed on rotating shafts. Solid components like sand and stones are removed in the first dry cleaning process. In the labeller, the label is removed from the bottles with sharp and jagged knives and blown into a collection chute. The PET Bottles are entering then into a pre-washing where larger and abrasive contaminants are removed, like labels and glues. Afterwards the bottles are sorted either manually or automatic by use of NIR and colour separation to ensure that different plastic types are sorted out. Unneeded materials are ejected with compressed air. In addition, a separation of bottles by colour is done, because colour has direct influence of the recycled PET. During the wet grinding bottles with the closure on it are cut into smaller pieces and a first hot washing is done to remove worst contaminants to avoid them in the more expensive chemically treated hot washing process. In the next section, finally polyolefins like HDPE are removed from the stream with a sink/float process. Polyolefins have a density below 1 kg/dm³ and will float, whereas PET has a density above 1 kg/dm³ and would therefore sink. Besides HDPE commonly materials like PE and PP can also be present here.
The PET stream on the other hand can still have contaminants of PVC and PA. It will be hot washed and chemically treated, dried and fines will be separated by elutriation. A final sorting is happening to eject alien materials and the stream is blended to increase homogeneity and decrease variability. Finally, PET flakes are stored in silos and packed in big bags or special trucks for shipment.
To conclude, our HDPE stream is most probably mixed with PP and PE coming from the today's established recycling stream. Whereas if we consider that in the countries where a DRS is in place today majority of the closures are made of HDPE, thus PP and PE would be very low in quantity.

5.4 Separation from other Materials

Majority of the bottles in Europe are sealed with a single piece HDPE cap, but some in some countries there are largely PP caps with a liner available (e.g. Portugal, Spain). These are countries with a warmer climate where the environmental stress crack resistance with a single piece closure is limited and to stay on the safe side they are using the heavier and stronger two-piece PP caps. Since PP has same as HDPE a density below 1 kg/dm³ it would also float during the separation process and contaminate the recycling stream of HDPE. That means if products are collected where potentially the HDPE cap stream could be contaminated with PP, there should be an additional step to sort out PP. Plastics Forming Enterprises LLC, a R&D laboratory, conducted trials and achieved a sorting efficiency of 95% utilizing NIR technology.

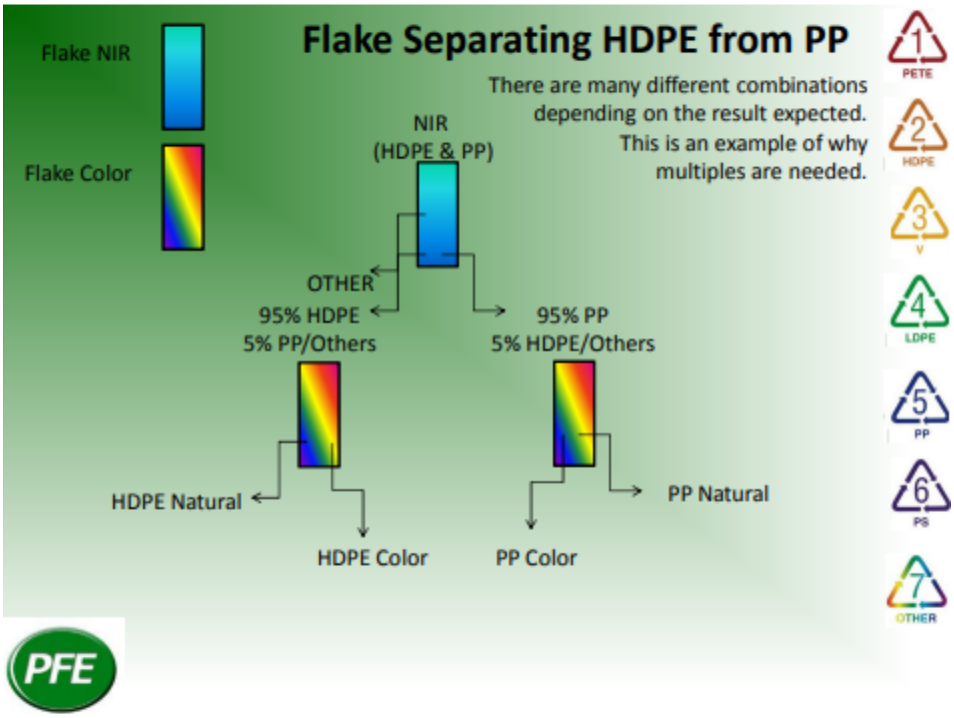


Figure 30: Separating HDPE from PP (PEF LLC. 2011)

5.5 Different Colours

Figure 31: Coke product line (CCEP, 2020)

Bottles are equipped with caps of different colours. A cap is the opportunity for a brand to communicate to the consumer by differentiating their product on the shelf and guide the consumer based on different colours belonging to different product ranges. For instance, Coca Cola is using different cap colours for their CocaCola product line. Sugarless products “Zero” typically have a black cap, whereas regular Coke gets a typical red Coke cap and “Light” Coke is featuring a silver one. Other than that special tastes like cherry are lemon are getting respectively a magenta red and yellow cap.

A small analysis has been performed in local supermarkets in France, Italy and Germany to understand the complexity of colours we have on the market. For the study, the quantity of different products on the shelf with different cap colours has been recorded, separated in the cap types CSD, Juice and Water. This has been done in order to separate by resin type group as explained in Figure 12. The separation was done in basic colours, of course, not all red caps have the same depth and different red colours exist on the market. It is also important to mentioned that only quantity of products has been recorded and not the total HDPE on the market with this colour, because it depends on the sales amount of the individual products.

We can see a clear tendency towards certain colours depending on the application and region. Overall, we can say that blue, red, green and white are quite famous colours for CSD caps, whereas for juice red, green and yellow are mostly used. For flat water blue, green, white and turquoise colours are the ones chosen by marketing to attract customers.

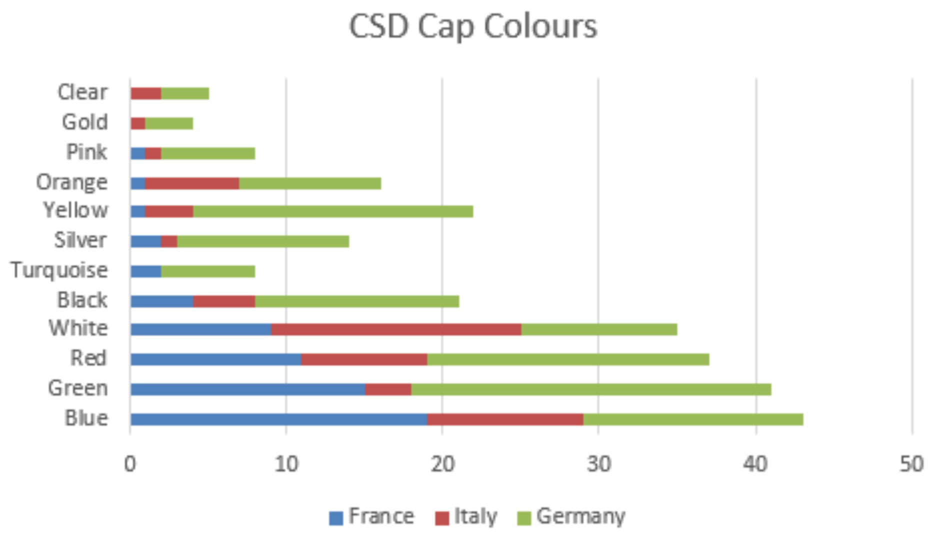


Figure 32: CSD Cap Colours

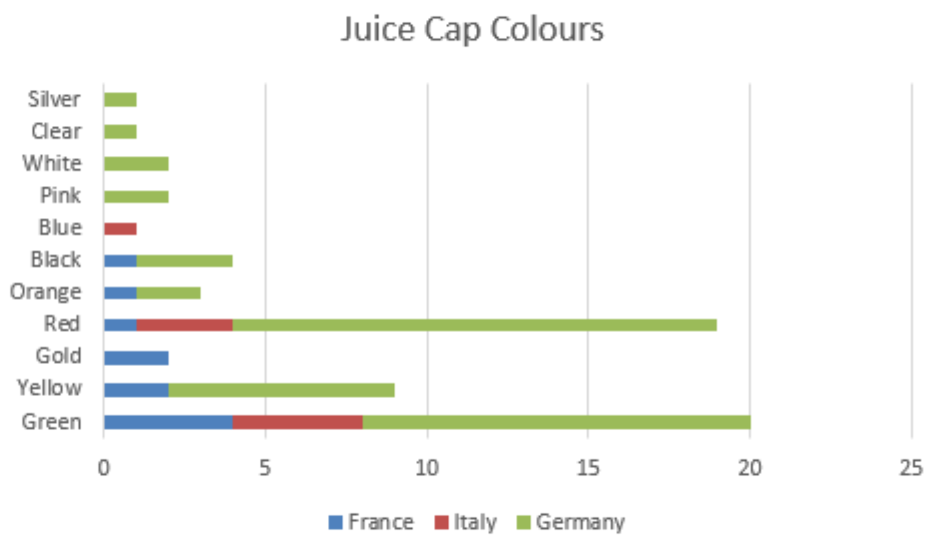


Figure 33: Juice Cap Colours

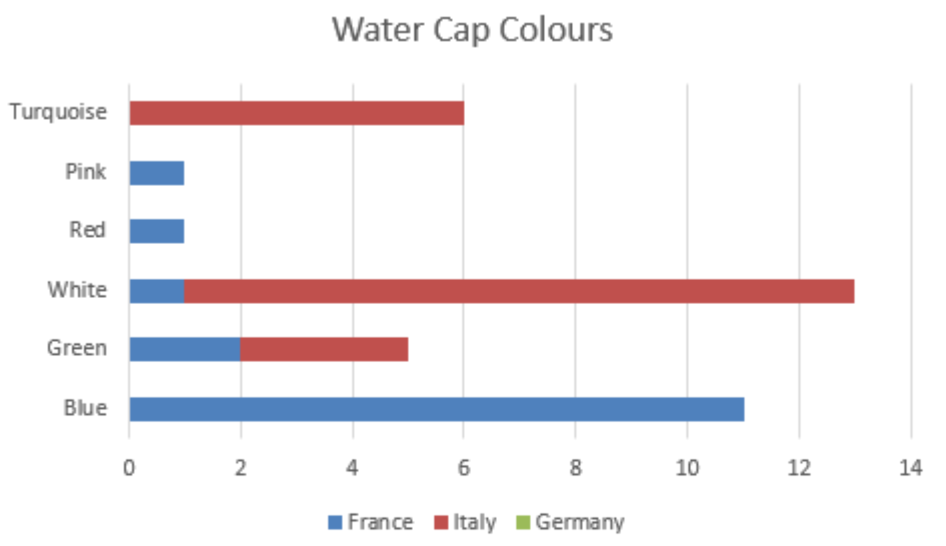


Figure 34: Water Cap Colours

Interestingly there is not a single water cap to see on the German market.

Even though different cap colours are a powerful tool for marketing departments to communicate to the consumer, but ultimately it creates a big headache for the recycling of caps. In the existing recycling streams there is no separation of bottles by cap colour happening as of today, thus the separation by colour has to happen after the bottles have been grinded, means at the base of HDPE flakes. Without a proper sorting of the HDPE flakes by colour, we would end up with an undefinable colour for caps that surely not many brand owners would be ready to use to seal their products, especially it would transfer a message of “uncleanness” to the consumer.

Sorting of HDPE flakes by colour can also be performed with NIR sorting. Several companies are offering sorting machines. However, for dark colours the sorting efficiency is quite poor, because they do not reflect light, but rather absorb it resulting in no signal arriving at the receiver. Other technologies would be laser spectroscopy that would allow more accurate sorting. Plastics are identified by their characteristics spectrum that, which is their physical fingerprint. Today such technology is used to separate for final sorting of PET flakes before granulation to make the RPET as clean as possible.

Nevertheless, a sorting for every colour type is technically limited and economically not viable. As previously mentioned there can be various types of red caps and a mix of them will result in a different red colour. Brand owners will need to accept that the closure will have a different colour type than what they are used to market their products.

5.6 Different Material Properties

After having HDPE flakes cleaned up from PP and sorted by colours, we have still the challenge that different grades of HDPE are used for different closure applications and even for the same application, different cap producers could use various HDPE grades for the same application. Typically, a certain closure design in combination with a certain resin/colorant is approved by bottlers. When changing any of them, a revalidation of every rHDPE is necessary for following reasons:

- Different resin grade has different properties in terms of injection velocity and shrinkage during moulding. This means if we change resin grade, the closure could change dimensionally and therefore its performance related to application and opening could be affected negatively
- Closures are designed to perform with certain resin grades related to their ESCR. The MFI is directly linked to it – the lower the MFI the better is usually the stress crack resistance. This is essential feature of CSD and Juice closures. When mixing different grades, MFI would alter and therefore ESCR would be effected and in worst case, the closure becomes not suitable for the corresponding application. On the contrary if an application like flat water, which requires a higher MFI for easier injectability due to thin side walls, will be injected with a lower MFI resin it would end up not injected fully (short shot).
- Some cap designs require a slip agent to achieve proper opening and closing performance. Typical slip agents for caps in the beverage sector are erucamide and behenamide, which are both food contact approved. However, erucamide is a less stable molecule and can migrate easier when exposed to light and temperature and alter the taste of a beverage. This is especially critical for flat-water applications. For that reason, some brand owners are allowing behenamide only for water. In addition, some markets like Germany are forbidding slip agents at all for water applications. That means if we have a mix of different grades that most probably contain slip agent, either behenamide or erucamide, it cannot be guaranteed what exactly will be in the recycled HDPE. Thus, specific applications with strict requirements will be excluded for the target market
- As initially introduced, HDPE grades are mono-modal or bimodal. Bimodal grades typically have the feature of a lower MFI, but still perform during injection like a mono-modal grade with much higher MFI. This allowed in the last decade to lightweight caps, while maintaining a good injection process window and closure performance, especially related to ESCR. An example is shared below which is an excerpt from a technical data sheet of Ineos for their grade ELTEX® Superstress™ CAP311, which has a MFI of 4 g/10min, but is performing a like a MFI 11 resin. If we mix all resins of a specific colour on the market together, we will have an unpredictable outcome of resin and potentially existing lightweighted designs are not suitable anymore.

Benefits & Features

- Very good injectability (MFR 11-like resin)
- High rigidity
- Good stress cracking resistance
- Improved rigidity/stress cracking resistance compromise
- Excellent quality controlled organoleptic properties
- Slip agent free grade

Applications

ELTEX® Superstress™ CAP311 is especially suited for applications requiring excellent processability, high rigidity and enhanced stress cracking resistance.. Thanks to high purity and excellent organoleptic properties it is well suited for packaging in direct contact with beverages and sensitive food.

- Injection Moulding and Compression Moulding of Caps & Closures for the packaging of still mineral water, juices and slightly carbonated or pressurized beverages

Properties	Conditions	Test Methods	Values	Units
Rheological				
Melt Flow Rate	190°C/2.16kg	ISO 1133-1	4	g/10min

Figure 35: CAP311 TDS excerpt (Ineos Group, 2022)

- Since we will have a mix of different resin grades, the question arises how stable the physical properties like MFI will be from batch to batch. It could well happen that in one batch the origin of closures is more from CSD applications what will result in a lower MFI, whereas if the origin of a batch contains more water closures, the MFI would be higher. A certain stability is crucial for a stable injection process and for closure performance. A high variation could make recycled HDPE useless for beverage caps application. For virgin resin production, this is kept under control by using time and amount of catalyst and temperature/pressure, thus a low tolerance can be kept.

It is obvious that mixing different resin origins is creating a headache for further processing into cap. Performance and safety are at risk and a potential redesign of existing caps on the market might be necessary to accommodate with new rHDPE grades.

5.7 Decontamination

Possibly the biggest hurdle is the possible contamination that can occur in HDPE after being consumed. When we speak about contamination, three different types of contamination can occur.

1. Physical contamination

Under physical contamination, we understand some solid parts like glass, wood, stones, metals and other components that can be mixed with HDPE after consumption of the beverage. During the sorting of PET bottles and on flake level majority of these physical contamination will be sorted out and should not be a problem (e.g. ferrous materials are sorted out with a magnet).

2. Microbiological contamination

Non-intended introduction of microbes, yeast, mould, fungi and virus can occur especially when mixed with biodegradable food waste. A proper collection method to separate upfront is reducing this risk drastically. Moreover, during an extrusion process of HDPE, where temperatures well above 200°C occur, all microbiological contamination is being removed. Microbes and bacteria are dying at such temperatures.

3. Chemical contamination

The biggest risk of contamination that is hard to remove in a recycling process is chemical contamination, which is coming from the presence of chemicals that should not be present in HDPE and have potential to migrate into the beverage that is expected to be consumed. The allowed chemical contamination is laid down in EU Regulation 10/2011. This type of contamination is not visible, is creating a possible harm to human health and creating odour of the product that is for our application of beverages critical because it can alter the taste. This is happening, because recycled plastics can produce volatile emissions that could be harmful or have negative impact on the packaged product (e.g. malodours). (SepSolve, 2023). These volatile emissions are called volatile organic compounds (VOCs). They are much more difficult to remove compared to solid parts, because they enter the polymer matrix and cannot be removed mechanically.

A study has been conducted on the amount of VOCs in virgin and recycled plastics. Figure 36 exhibits the amount of VOCs of plastics in different stages. From virgin material (Virgin), manufactured (Man), post industrial waste (PI) and post-consumer waste (PC). It is very clear that the main increases are on hydrocarbons (HC), flavour and fragrance, alcohol, aldehyde, acid and ester.

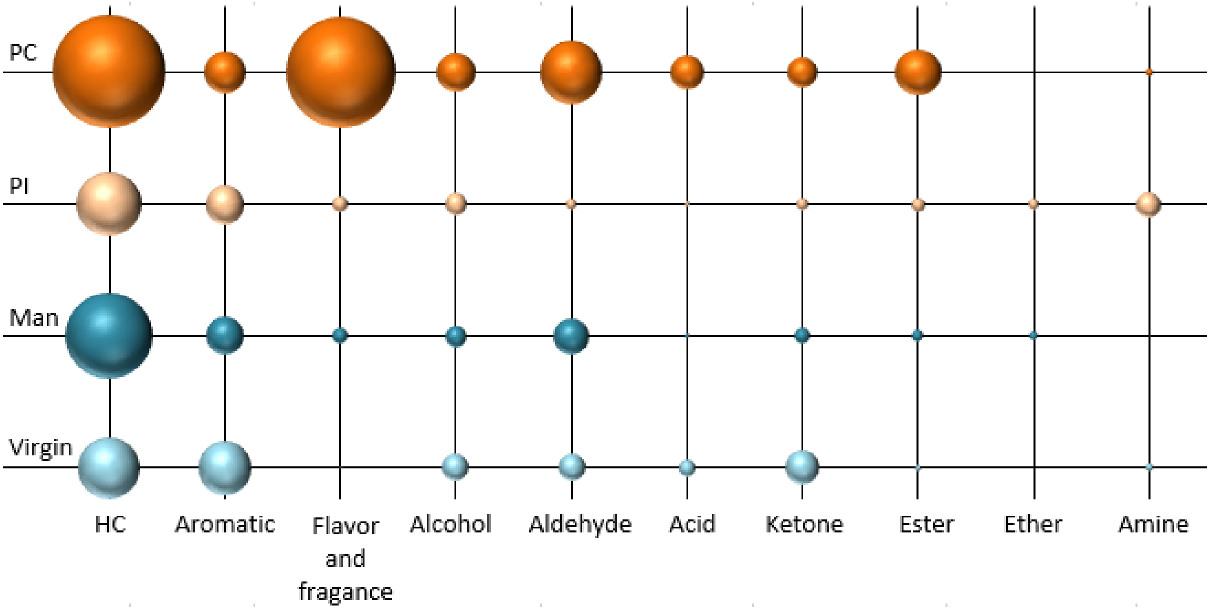


Figure 36: VOCs Plastics (A. Cabanes, F.J. Valdés and A. Fullana, 2019)

a) Hydrocarbons: organic chemical compound consisting only of carbon and hydrogen elements
b) Alcohols: carries at least one hydroxyl (OH-) functional group that is bond to a saturated carbon atom. On the site of the OH group many reactions can occur.
c) Aldehydes: a carbon, which atom shares a double bond with an oxygen atom, a single bond with hydrogen and a single bond with another atom. The characteristics of this group is the double bond between carbon and oxygen.
d) Acids: named carboxylic acids, consisting of a carbon atom that has a double bond with oxygen, a single bond with OH and with fourth bond with another atom.
e) Esters: created by a reaction of an acid and alcohol while dehydrating. The formula would be RCOOR’ with R and R’ as any organic compound

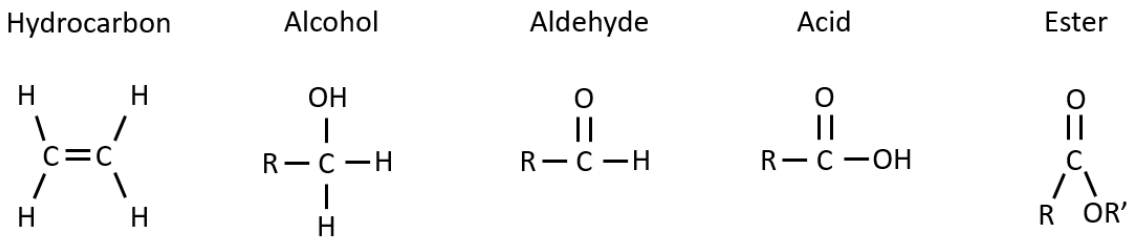


Figure 37: Chemical Compound of main VOCs

The main components of all VOCs are hydrogen, carbon and oxygen, same as HDPE is consisting of carbon and hydrogen. The first question that appears is why these molecules are all attached to HDPE. The interaction here is not a regular bond between molecules and sharing electrons (ionic), but a so-called van der Waals force, which is a relative weak electric force compared to ionic forces that attract molecules to each other. Following schemes are possible:

- Permanent electrical dipoles, where one side of the molecule is positive and another negative, tend to align with each other that results in a net attractive force

- A permanent dipole changes by induction the polarity of a nearby polar or non-polar and attracts it
- Even if we have two non-polar molecules a certain attraction is occurring, because electrons are moving around create a temporary dipole of a non-polar molecule and therefore change the polarity by induction of the neighbour non-polar molecules. For example: if we assume that a molecule is getting temporarily positive on one side it will attract the electrons of another non-polar molecule and a certain electrical force will be created between the temporary positive and induced negative sides of the molecules

(The Editors of Encyclopaedia Britannica, 2023)

To achieve these states a relative low temperature is required to attract binding of the molecules, this is especially the case when non-polar molecules interact. However, to break this force something has to happen to make the electrons move again, like induced temperature. This is also the reason why in today is mechanical recycling technologies a decontamination is happening at a certain temperature and time after pelletizing in a reactor.

As of today only PET is approved by the EFSA for mechanical recycling, thus the differences between PET and HDPE will be drawn to understand why HDPE recycling is so challenging regarding decontamination:

1. Different melting point

HDPE has a melting point of 130°C, whereas PET has 260°C. We know that to release VOC we need to break the Van der Waals forces that require temperature and time, thus the efficiency of HDPE decontamination would be already lower due to lower temperature applicable in the reactor. The WHO is classifying VOCs further into VVOC (Very Volatile Organic Compounds) with a boiling point of 100°C, VOC with a boiling point between 100°C and 160°C, and SVOC (Semi Volatile Organic Compounds) with a boiling point between 260°C and 400°C. (A. Cabanes, F.J. Valdés and A. Fullana, 2019). Being closer to the boiling point makes them release faster and due to the lower possible operating temperature of HDPE we are limited in decontaminate regular VOCs.

2. Van der Waal forces difference

The PET molecule has 10 carbon atoms and if we would consider a HDPE chain with the same amount, it would result in an overall larger surface because the HDPE chain is linear, where more interaction of Van der Waal forces can happen. That means that HDPE is by default attracting more volatiles, because the Van der Waals forces are higher. That means that possible contamination can be higher.

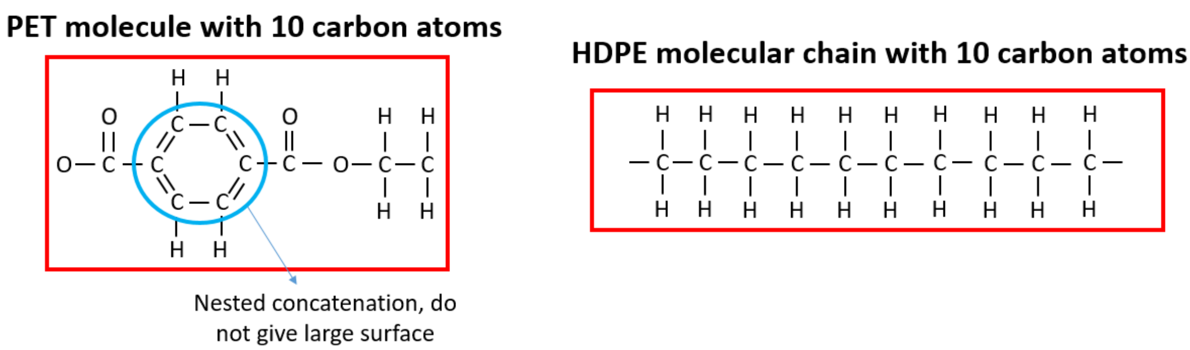


Figure 38: Molecular Surface of HDPE and PET

3. Free Volume Space

One of the most significant differences is the free volume space that HDPE and PET can provide. HDPE has a linear structure, so if we are putting them together it is like having arrays of drumsticks together, which do not leave too much free volume between the molecular chains where the VOCs can find their place. On the other hand, PET that is used today for beverage bottles production is a Copolymer, so PET with co-monomers added to enhance properties that are changing the molecular chain, not being straight anymore but rather in a “wavy” chain.

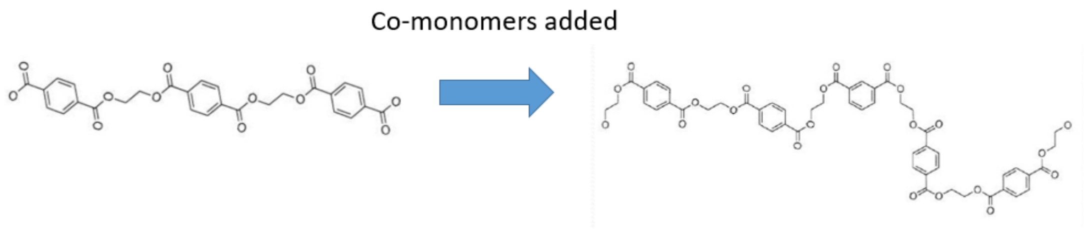


Figure 39: Copolymer chain

Packed together, PET is leaving more space, which is visualized in Figure 40. The diffusion of molecules from the free space is known as the “free volume theory”. Diffusion of these molecules is described as a random redistribution of free volume voids, which is thermally activated. Temperature reflects the movement of the chains and is increasing the diffusion of VOC, this is also, why during mechanical recycling with increased temperature we can extract more VOCs, because the movement is greater and the chance for diffusion increases. (Sabu, G.C. Soney, S. Thomasukutty, 2020)

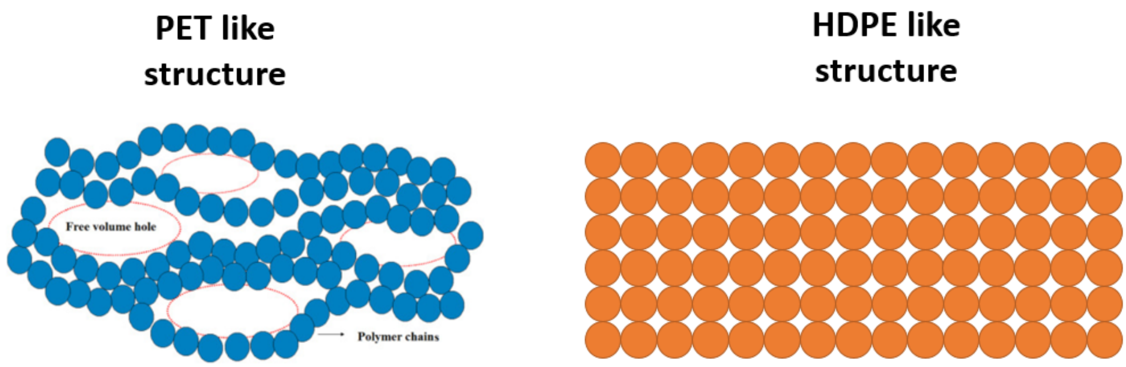


Figure 40: PET and HDPE molecular structure

Knowing these three challenges, we can clearly conclude that HDPE is by far more challenging in terms of chemical decontamination than todays approved PET mechanical recycling.

5.8 Molecular Changes of HDPE after Extrusion

Another challenge for HDPE recycling are the possible changes of the molecular structure that can occur during the extrusion, which is a crucial part of mechanical recycling of polymers. As we learned previously, HDPE is linear with no or low branching. However, during the extrusion process some thermally induced changes happen that are changing the molecular weight and/or the linearity of HDPE.

HDPE is extruded at temperatures above 200°C, where it is inevitable that pressure is created and changes happen to the HDPE molecules. Within the polymer chain of HDPE, we have carbon atoms that bind the electron of hydrogen atoms. Since the electronegativity of carbon is higher, it will pull the electron closer, creating a slight positive charge on the hydrogen atom. Due to the higher temperatures and pressure, hydrogen is able reacquire the electron, it would detach from the carbon atom and become a radical (definition below). Since within the HDPE chain, now one hydrogen atom is missing and the carbon atom requires now an electron to bind, there is given the possibility to cross-link with another HDPE chain, which is in the same state.

Definition of a free radical: A free radical can be defined as any molecular species capable of independent existence that contains an unpaired electron in an atomic orbital. The presence of an unpaired electron results in certain common properties that are shared by most radicals. Many radicals are unstable and highly reactive. They can either donate an electron to or accept an electron from other molecules, therefore behaving as oxidants or reductants (V. Lobo & A. Patil & A. Phatak & N. Chandra, 2010).

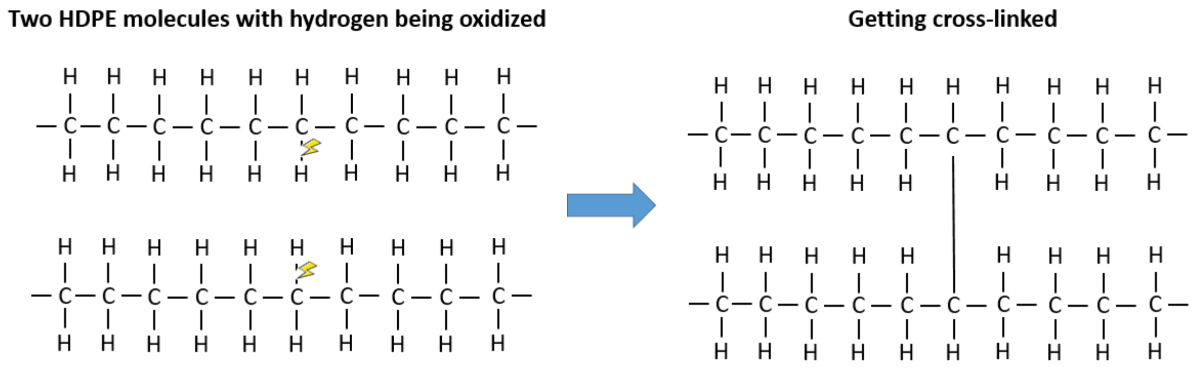


Figure 41: HDPE Cross-Linking

Another possibility is the chain scission, where the bond between the carbon atoms is broken. Basically, we have here a reversible reaction happening compared to the production of HDPE. During production of HDPE, a free radical is breaking the double bond of between carbon atoms of ethylene by attracting one of the electrons, which is creating a reaction chain in attracting other ethylene monomers to form the backbone of hydrogen and carbon. Only once a reaction happens with another chain in polymerization phase, the growths of the HDPE chain stops and the HDPE chain is fully developed. Now in our case, the reaction is going in the other direction, which due to temperature and pressure we break the carbon bond and free radicals are closing these broken chains.

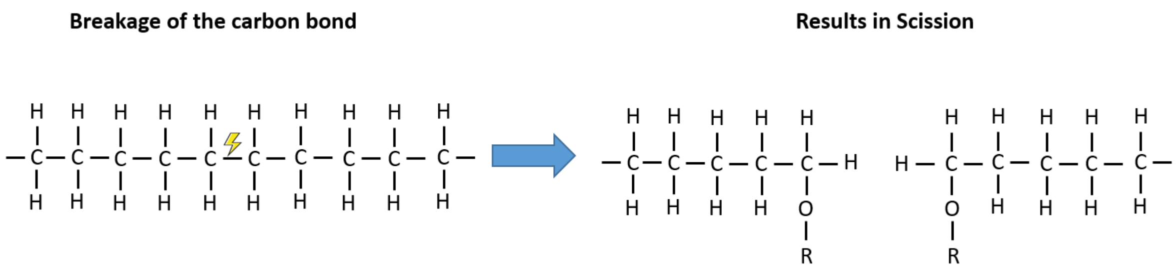


Figure 42: HDPE Scission

Both, the scission and the cross-linking, are changing the molecular weight of HDPE and therefore the MFI. The possible effects of these are summarised in chapter 5.6.

These reactions can be stopped and/or reduced by stabilizers. A wide variety of "stabilizers" have been developed to reduce the changes (e.g., crosslinking) that can occur during melt processing or under conditions of use. Many of the stabilizers are organic compounds, which are classified in the plastics industry as antioxidants. (SpecialChem, 2023)

5.9 MSP Solution

Morssinkhof Sustainable Products, one of the largest recycling companies in Europe headquartered in Netherland, developed a certain process for HDPE cap2cap recycling that is under validation and described in this Thesis.

The input material is coming from deposit return systems in Germany, Netherland and Scandinavia, which means the bottles collected are solely coming from food application and is providing a very clean source of bottles with low contamination.

In the first step, the bottles are sorted by colour and polymer type by utilizing NIR sorting technology. In this step, it is ensured that only PET bottles will be processed in further downstream and colour sorting ensures a certain level of control of RPET colour. Usually clear, green and blue bottles are separated and used to produce further RPET for the beverage industry. Other, more difficult to recycle colours like opaque coloured bottles are usually going to less demanding applications like strapping and are not fulfilling the intended circular economy requirement. The label is removed with a label separator and bottles enter afterwards into a wet grinding, where bottle and cap together become flakes, so we have now a mix of PET and HDPE flakes. After a first cold washing operation, where major dirt on the flakes is removed, the flakes are entering into a density separator, where PET and Polyolefins are separated in water. PET has a density greater than 1 kg/dm³ and would sink, whereas Polyolefins that have a density below 1 kg/dm³ would float.

The output is a stream of PET that is going further into the downstream of PET recycling. The Polyolefin section is mainly consisting of HDPE, because firstly, the label that can contain Polyolefin was separated earlier and secondly the bottles received from the deposit systems from Germany, Netherland and Scandinavia are mainly equipped with caps made from HDPE and not PP. PP is in the EU region mainly present in the warmer regions like Spain and Portugal, where ESCR might be an issue with HDPE caps due to high environmental temperatures. The stream of HDPE is a mix of several colours, which is as of today sold to pallet makers for the food industry and with the new process, should be upcycled to be allowed for usage for injection of caps allowing a circular economy.

The different colours can be sorted by using NIR technology again (except for black, where NIR is not applicable). This operation is frequently happening twice to ensure that in a red section of HDPE as much red as possible is contained, because the sorting technology is not providing a 100% efficiency in terms of sorting and with every additional run-through, the purity is increasing. However, the sorting is a quite expensive operation and it is recommended to limit it as much as possible. Thus, the intended process is to focus only on sorting red and blue colours that are easier to sort and in addition are representing a large amount of all HDPE caps. All the other colours will be left mixed together and are intended to be used with black colourant and for the production of black caps (black masterbatch is added during plastification of HDPE before injection).

That means we result in three HDPE streams with red, blue and mixed colours, which are then hot washed to remove residual glues, oils and greases to provide a clean stream of HDPE. The flakes are then entered into the extrusion process, which is a twin extruder with vacuum degassing. The goal of the extrusion is to homogenize HDPE and make it from chemical and physical perspective cleaner. The extruder is set-up with a special temperature profile between 200-220°C. Since we add HDPE flakes, we have some air that is occupying the space between the flakes. These needs to be degassed after the flakes went over completely into melt phase. The extraction of gases is occurring in the degassing zone of the extruder by using vacuum. A positive effect of this degassing is that the more volatile are VOCs are extracted here, because we run at relatively high temperatures and as we learned due temperature the molecular chains start to move and VOCs can be extracted. During the extrusion process, an additive will need to be added to avoid cross-linking and scissoring of the HDPE chains.

After being extruded, the melt is pelletized. The process here to get pellets is quite simple: HDPE is extruded into strings and then cooled down under water and cut into pellets. This step is important, because cap producers are using standard injection moulding machines for cap manufacturing, which cannot process flakes due to their low bulk density.

In the last stage, the HDPE pellets will be decontaminated further with the goal to get as many more difficult to remove VOCs out as possible. For this, two technologies can be used:

- Vented Hopper: HDPE will be loaded into a hopper that is under atmospheric conditions and will be flushed with hot air at 80°C. Temperature of HDPE is increased and the more difficult to remove VOCs are extracted. Using this technology, we will need to consider up to 15 hours residence time in the vented hopper.
- Post-Condensation with a reactor: HDPE is loaded into a hopper that is under vacuum and possibly nitrogen, which is allowing a lower level of degradation due to missing oxygen. Temperatures can be slightly higher and therefore the residence time can be reduced down to 6 hours.

The finished rHDPE is ready to be packed into big bags and shipped to the cap producers to be injected again.

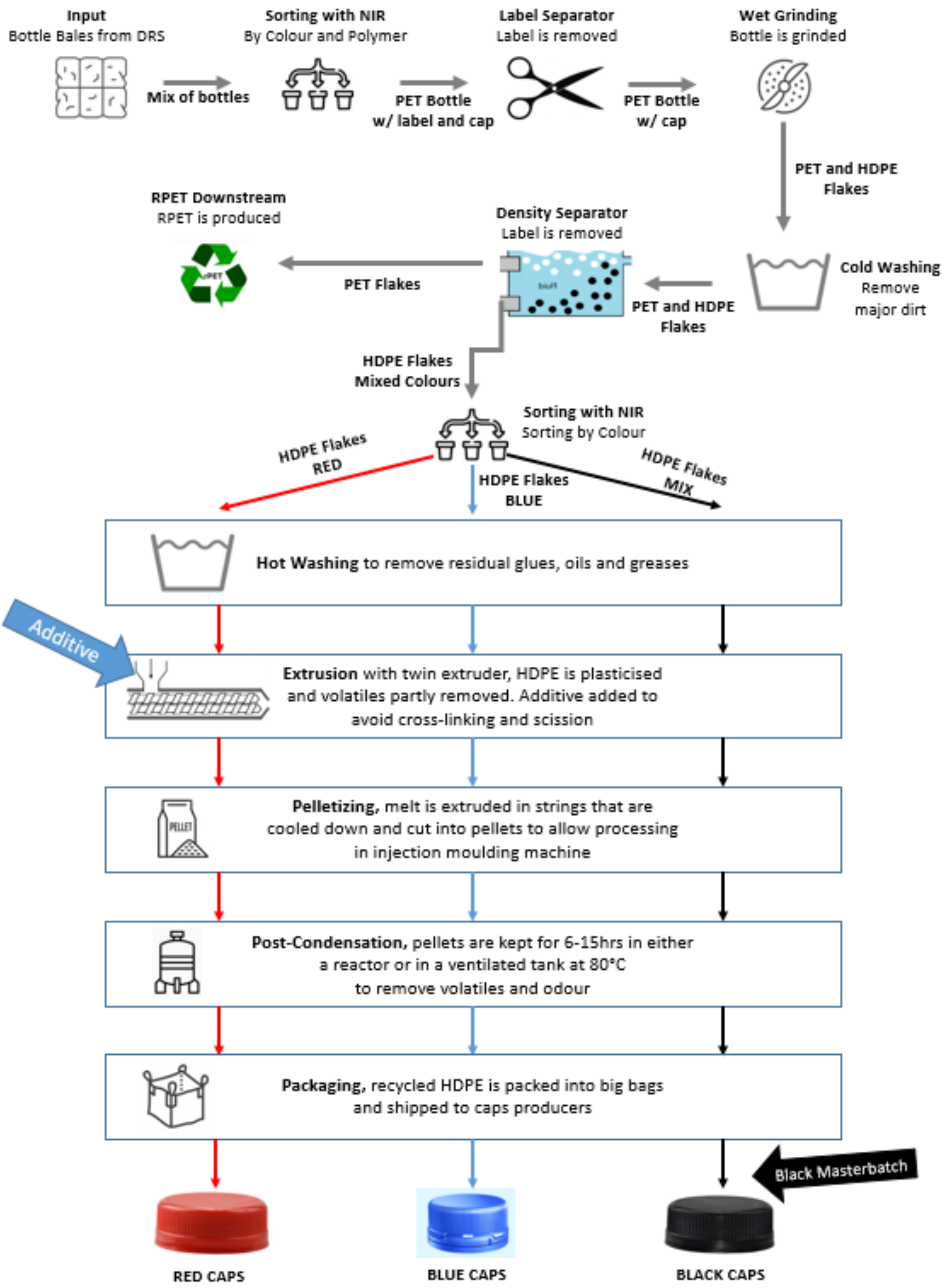


Figure 43: MSP HDPE recycling process

6. Economical Analysis

From the technical analysis we understand that we have at least a theoretical possibility to get HDPE clean enough to use it for food applications, provided that adequate collection, sorting and decontamination is applied. However, to make HDPE cap2cap recycling attractive for the industry they need to make money out of it. In this chapter we will analyse the required investment in capital equipment, what is the rate to convert post-consumer HDPE into food approved rHDPE and possible payback time of the investment.

Since there can be different business models and players in this field, three different cases will be analysed for the payback calculation:

1. Complete new business who needs to acquire building and all the equipment
2. Existing recycling facility that is today already specialised on sorting
3. Existing recycling facility that is today already recycling HDPE for other applications and therefore has all the required equipment in place

6.1 Investment Overview

We start in the process after the separation of PET and HDPE, which is as of today already in place, and feeds our recycling process with HDPE of mixed colours. We would need one density separator and hot washing machine, one extrusion and pelletizing unit and one post-condensation to clean the HDPE pellets. To have enough sorting capacity to sort by different colours, we will require six NIR sorter. The prices in the table have been aligned with MSP based on their experience.

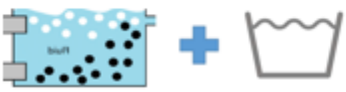
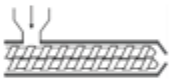
Investment Cost	Quantity	Price
Density Seperator + Hot Washing 	1	3.000.000 €
NIR Sorter 	6	1.500.000 €
Extrusion and Pelletizing 	1	2.500.000 €
Post-Condensation 	1	2.000.000 €
Total Machinery Investment		9.000.000 €
Building – 2000sqm 	1	2.600.000 €
TOTAL RECYCLING FACILITY		11.600.000 €

Figure 44: Investment Overview

6.2 Total Cost Ownership

The TCO calculation will be done based on "per ton" and considering full utilization of the production equipment. The investment in equipment and building is based on an output of 10,000 tons per year. This type of equipment is giving an efficiency of 95% at a scrap rate of 3%, resulting in a total output of 9.215 tons per year. Following operational data have been gathered during an interview with Matthijs Veerman, Business Development Manager at Morssinkhof Sustainable Products:

- Efficiency Rate: 95%
- Scrap Rate: 3%
- Gas Consumption for Hot Washing: 100 kWh/ton
- Electricity consumption Extrusion + NIR: 500 kWh/ton
- Post-Condensation Consumption: 225 kWh/ton
- Annual Maintenance Cost for Equipment as % of Investment: 7%
- Required Floorpsace: 2000sqm
- Big Bag Cost: 15 Euro
- Pallet: 15 Euro
- Hood: 5 Euro

(Veerman M., 2023)

Operating main conditions	**Unit**	
Output per year	tons	10.000
Efficiency	%	95%
Scrap Rate	%	3%
Total Output per Year	tons	9.215

Figure 45: Operating Conditions

1. Financial Cost

As financial cost, we understand the interest paid for the required investment. For the sake of easier calculation we assume for the TCO hat 5% interest is paid on the whole amount. For equipment, we take 10 years of depreciation time, which gives us based on 9 million Euro investment a depreciation per year of 900.000 Euro, resulting in in interest per year of 45.000 Euro and a total equipment financial cost of 945.000 Euro per year. For the building depreciation time of 40 years is considered, that gives us a depreciation cost of 65.000 Euro per year. The sum of the financial cost 945.000 Euro plus 65.000 Euro is divided by the total output per year of 9.215 tons is resulting in 110 Euro per ton as total financial cost.

Financial Cost	Unit	
Equipment Depreciation Time	Years	10
Equipment Depreciation per year	EURO	900.000 €
Equipment Capital Interest per year	%	5%
Equipment Capital Interest per year	EURO	45.000 €
Equipment Financial Cost per year	EURO	945.000 €
Building Depreciation Time	Years	40
Building Depreciation per year	EURO	65.000 €
Financial Cost / ton	**EURO**	**110 €**

Figure 46: Financial Cost

2. Energy Cost

The overall process is very energy intensive, where we need 10m³, equalling to 100 kWh gas per ton of HDPE for the hot washing process. At an average price of 0.09 EUR per kWh, we require 9 Euro per ton of HDPE for gas. For the remaining process of sorting, extrusion and post-condensation the electricity consumption is 725 kWh per ton. Electricity price is 0.25 EUR per kWh, resulting in 181,30 Euro per ton. This results in a total energy cost of 190.3 Euro per ton of HDPE for energy. Gas and electricity prices are based on Eurostat prices for first half of 2022.

Energy Cost	Unit	
Gas Consumption for Hot Washing	kWh/ton	100
Gas Price per kWh	EURO	0,09 €
Total Gas Cost per ton	EURO	9,0 €
Electricity consumption: Extrusion + NIR	kwh/ton	500
Electricity consumption: Post-Condensation	kwh/ton	225
Total Electricity Consumption	kwh/ton	725
Electricity Price per kWh	EURO	0,3 €
Total Electricity Cost per ton	EURO	181,3 €
Total Energy Cost per ton	**EURO**	**190,3 €**
Total Energy Cost per year	EURO	1.753.154 €

Figure 47: Energy Cost

3. Operators Cost

In this business due to the high throughput and long start-up procedures for extrusion and increased scrap rate due to re-starts of machinery a 24/7 operation is targeted. We calculate here with 4 operators per shift working in 4 shifts, resulting in 16 workers required. As base, we take 50.000 Euro salary per worker. This results in operators cost of 87 Euro per ton.

Operators Cost	Unit	
Total Operators per Shift	#	4
Shifts	#	4
Annual Salary per Worker	EURO	50.000 €
Total Manpower Cost per Year	EURO	800.000 €
Operators Cost per ton	**EURO**	**87 €**

Figure 48: Operators Cost

4. Maintenance Cost

For the machinery, we consider annual maintenance costs of 7% of the investment, results in 630.000 Euro. For the building, we take 28 Euro per square metre, which gives us annual costs of 56.000 Euro based on 2.000 square meter space required. In total, we are reaching 74 Euro in maintenance cost per ton.

Maintenance Cost	Unit	
Annual Maintenance for Equipment as % of Investment	%	7%
Annual Maintenance Cost for Equipment	EURO	630.000 €
Building Maintenance Cost per sqm	EURO	28 €
Floorspace	sqm	2.000
Annual Maintenace Building Cost	EURO	56.000 €
Total Maintenance Cost per ton	**EURO**	**74 €**

Figure 49: Maintenance Cost

5. Sales, Logistics and General Expenses

We would personnel to make several tasks like sales, administration and logistics. Overall, we calculate 250.000 Euro per year for salaries and expenses here, resulting in 27 Euro per ton.

Sales, Logistics and General Expenses	Unit	
Expenses per year	EURO	250.000 €
G&A Expenses per ton	**EURO**	**27 €**

Figure 50: G&A Cost

6. Packaging Cost

Ultimately, we have to pack the recycled HDPE after the post-condensation. In the recycling business, it is common to use big bags for this. In one big bag, we can typically fit one ton of resin, where a hood is applied and put on a pallet. We get a total packaging cost of 35 Euro per ton.

Packaging Cost	Unit	
Big Bag	EURO	15 €
Pallet	EURO	15 €
Hood	EURO	5 €
Packaging Cost per ton	**EURO**	**35 €**

Figure 51: Packing Cost

The sum of all these costs gives us 523,20 Euro per ton. That means to convert one ton of HDPE flakes to pelletized HDPE of food grade we require this amount of money.

Financial Cost / ton	**EURO**	**110 €**
Total Energy Cost per ton	**EURO**	**190,3 €**
Operators Cost per ton	**EURO**	**87 €**
Total Maintenance Cost per ton	**EURO**	**74 €**
G&A Expenses per ton	**EURO**	**27 €**
Packaging Cost per ton	**EURO**	**35 €**
TOTAL COST per Ton	**EURO**	**523 €**

Figure 52: Cost Summary

It is quite evident that energy is representing the biggest cost factor for the conversion with 36%. That means putting efforts on contracting energy in cheapest way will secure a competitive advantage. It shows also a possibility for countries in Eastern Europe with lower energy cost to be more competitive in this business or for instance countries like France where energy is heavily subsidised by government.

Besides energy the second biggest factor is financial cost with 21%, followed by operators cost with 17%. On the financial side there is not a lot that can be done, heavy investment is simply required to stablish such massive operation. However, on the operators cost countries in Eastern Europe can be also of an advantage. Maintenance cost represent 14% of costs and lastly packaging and G&A expenses with respectively 7% and 5%.

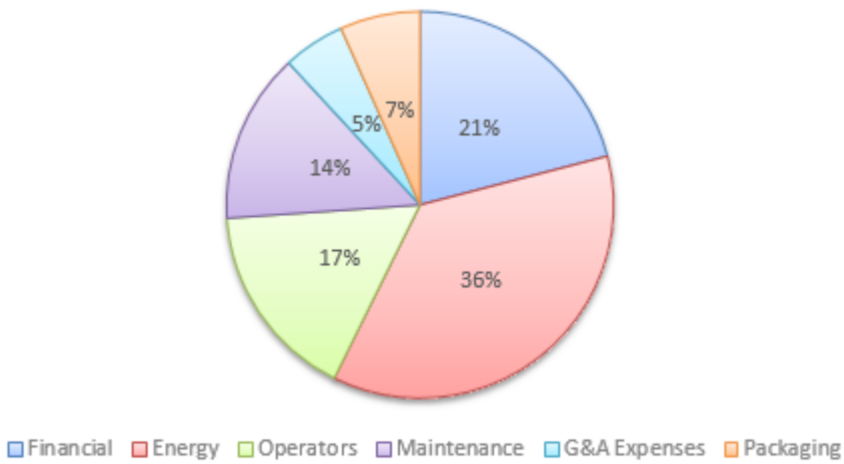


Figure 53: TCO Analysis

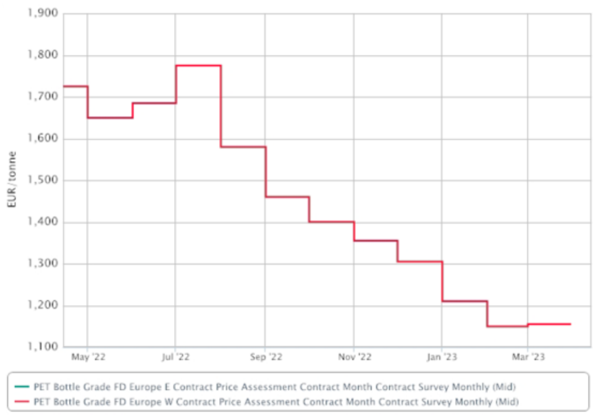
6.3 Profitability Analysis

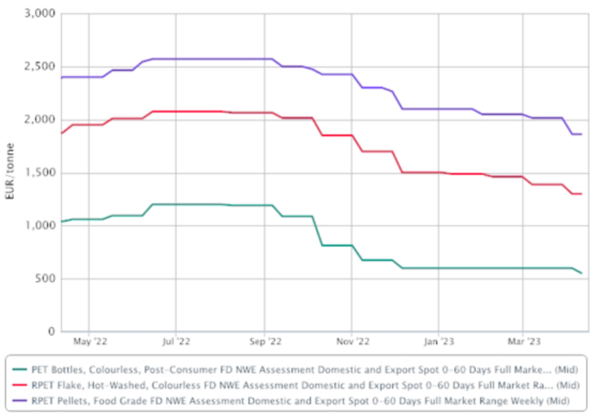
The logic question that arise now is, is this conversion rate competitive? To answer this question we need to make a comparison of what is today happening with the HDPE flakes and what can be the possible sales price.

As of today, HDPE flakes are sold to less demanding applications like plastic pallets, which are coloured black anyway, so they do not care if the HDPE is a mix of different colours. It is a good alternative for pallet producers using this material, because they can source it cheaper than virgin

HDPE resin. Typically, they buy the HDPE flakes 80% of the virgin price. That means in our business case to upcycle HDPE to cap injection application we need to compete with the current sales to pallet producers and it must be more profitable to convert food contact grade for cap production rather than simply selling at 80% of virgin price.

The opposite logic would apply in the beverage industry, where brand owners are ready to pay a premium for having a more sustainable product, because they can market their products in a different way and attract more consumers who are very sensitive to sustainability these times. We have for instance Coca Cola running with 100% recycled PET in several countries being one of the pioneers in introducing a more sustainable packaging and thus gaining competitive advantage. From RPET sales, as per Morssinkhof Sustainable Plastics, brand owners are ready to pay a 50-100% premium compared to virgin PET. This also proven by the numbers of ICIS (Independent Commodity Intelligence Services). If we analyse the virgin PET and RPET prices in the period between May 2022 and March 2023, we can see that the premium in that period was actually 45% – 80%.





	PET	RPET	Spread	Premium
May '22	1.650 €	2.400 €	750 €	45%
Jul '22	1.690 €	2.600 €	910 €	54%
Sep '22	1.470 €	2.600 €	1.130 €	77%
Nov '22	1.360 €	2.450 €	1.090 €	80%
Jan '23	1.210 €	2.100 €	890 €	74%
Mar '23	1.160 €	2.050 €	890 €	77%

Figure 54: ICIS Data (Murray C., 2023)

The exact premium depends on availability and demand. Currently many prognosis are giving a decline in the premium, because due to increased prices and inflation, consumers are more price sensitive and consume in general less. Our assumption therefore, is that similar logic would apply to rHDPE and we assume a premium between 50% and 100% compared to virgin HDPE. Figure 46 is showing the virgin HDPE price from April 2022 until March 2023.

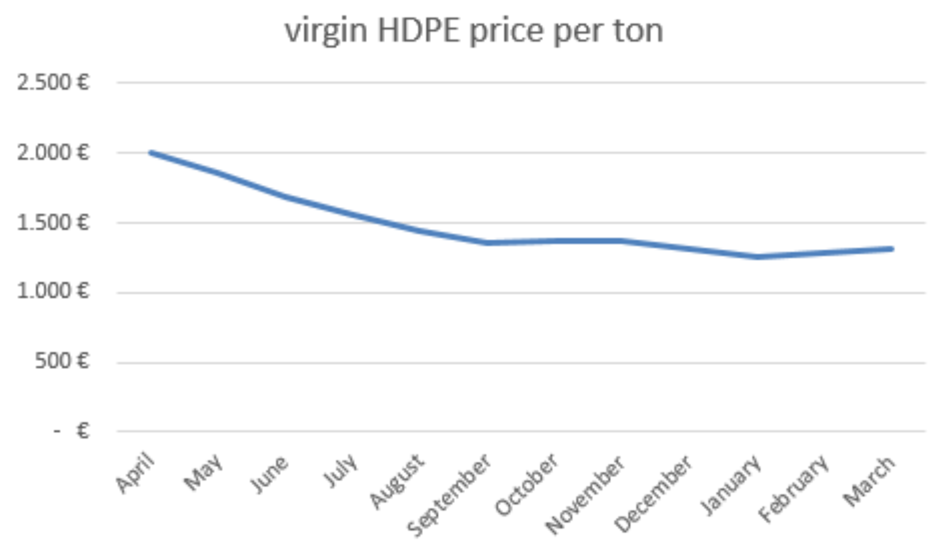


Figure 55: virgin HDPE prices

The price decreased from 2.000 Euro to 1.310 Euro (source: myCEPPI, Market Prices for Commodities in Central and Eastern Europe). The average over 12 month was 1.483 Euro, so we will take the last 12 months average for further calculations.

In the calculation, all prices are shown per ton. The input material in our process is at 80% of the virgin HDPE price, equalling 1.186 Euro per ton and is converted at the previously calculated 523 Euro per ton. This is giving us a total product cost of 1.709 Euro per ton. The Premium we can apply on the virgin price is 50% (= 742 Euro) and 100% (= 1.483 Euro), giving me us respectively possible sales prices of 2.225 Euro and 2.966 Euro per ton, resulting in profit between 515 (= 23%) and 1.257 (= 42%) Euro per ton.

Premium	50%	100%
Virgin HDPE price	1.483 €	1.483 €
Input Material (80% of virgin price)	1.186 €	1.186 €
Conversion	523 €	523 €
Cost to Produce (incl raw input material)	1.709 €	1.709 €
Premium in Euro	742 €	1.483 €
Sales Price	2.225 €	2.966 €
Profit	515 €	1.257 €
Profit (%)	23%	42%

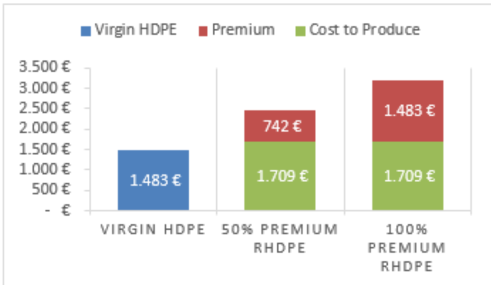


Figure 56: Profitability rHDPE

The limitation here remains that not only virgin prices can fluctuate, but also energy prices, which would change the calculation significantly. Nevertheless, these numbers give a good indication. We can clearly see that in terms of profitability of the business it makes sense to produce rHDPE based on the virgin prices of the last 12 months. However, virgin prices depend on crude oil prices and we know that in the last two years prices have been skyrocketing. If we look at Figure 48, which are showing historical HDPE injection grade process for Northwest Europe, which are pretty much in line with prices from Figure 46 for 2022. However, in beginning of 2020 we see very low prices in the range of 900 $/ton, which equal around 750 Euro/ton based on the exchange rate end of 2020. This leads to the natural question, how profitable we would be if prices would drop heavily again.

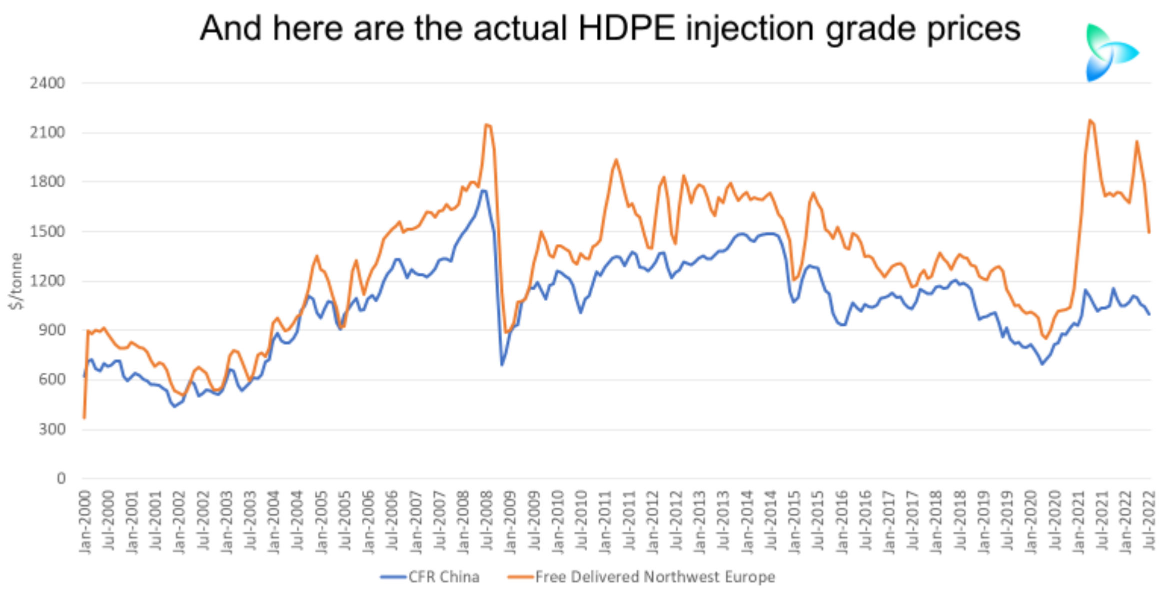


Figure 57: HDPE historical prices (John Richardson, 2022)

Therefore, it is important to understand at which virgin price we would breakeven. Our sales price is following a very basic formulate based on virgin HDPE price. Sine we want to analyse the lowest possible point, we will also assume a premium of 50%. The breakeven point is achieved when our sales price would equal our costs, which means our profitability would be zero.

$$Sales\ Price\ =\ Virgin\ Price\ +\ 0.5\ x\ Virgin\ Price\ =\ 1.5\ x\ Virgin\ Price$$
$$Cost\ =\ 0.8\ x\ Virgin\ Price\ +\ 523\ Euro$$

$$Sales\ Price\ =\ Cost$$
$$1.5\ x\ Virgin\ Price\ =\ 0.8\ x\ Virgin\ Price\ +\ 523\ Euro$$
$$0.7\ x\ Virgin\ Price\ =\ 523\ Euro$$
$$Virgin\ price\ =\ 523\ Euro\ \div\ 0.7$$
$$\boldsymbol{Virgin\ Price\ =\ 747.14\ Euro}$$

The calculation shows that at a virgin price of 747.14 Euro per ton virgin HDPE price we would start to become unprofitable, considering a premium for recycled material compared to virgin. This means in 2020 when the last low price was reached we would be just at the border. This is bringing a clear risk to this business model to be not able to compete with virgin grades.

6.4 Payback

For the payback calculation, we will use profit 515 Euro per ton, calculated in figure 47 with 50% premium. We consider a fully booked production line with 9.215 tons output. As mentioned previously, there can be different business models where different investments would be required:

1. Complete new business with investment in all production equipment, which equals 11.6 million Euro as per figure 44. In this case, business operator would purchase HDPE flakes to produce recycled HDPE of food contact grade.

Investment Cost	Quantity	Price
Density Seperator + Hot Washing	1	3.000.000 €
NIR Sorter	6	1.500.000 €
Extrusion and Pelletizing	1	2.500.000 €
Post-Condensation	1	2.000.000 €
Total Machinery Investment		9.000.000 €
Building - 2000sqm	1	2.600.000 €
TOTAL RECYCLING FACILITY		11.600.000 €

Figure 58: Investment new recycling facility

Production Volume (tons)	9.215
Profit per ton (Euro)	515 €
Total Profit per year (Euro)	4.745.725 €
Payback (years)	2,44

Figure 59: Payback new recycling facility

The calculation is giving us a payback of 2.44 years, which is very good considering the high investment into production machines and building.

2. The second business model would be a waste manager, who is using today already separation and sorting technologies and is selling different plastic grades, that are non-food yet. A Building also exists and only the extrusion, pelletizing and post-condensation would need to be added. We assume that equipment is of large enough output that the additional 9.215 tons can be processed, same as the existing building is large enough to put the additional equipment. Another assumption is that the TCO will not change, what in reality most likely is not going to happen, because with higher output usually the cost per ton would decrease. Profit and production volume are considered the same like in case 1.

Investment Cost	Quantity	Price
Extrusion and Pelletizing	1	2.500.000 €
Post-Condensation	1	2.000.000 €
Total Machinery Investment		4.500.000 €
TOTAL RECYCLING FACILITY		4.500.000 €

Figure 60: Investment existing recycling facility

Production Volume (tons)	9.215
Profit per ton (Euro)	515 €
Total Profit per year (Euro)	4.745.725 €
Payback (years)	0,95

Figure 61: Payback existing recycling facility

With a payback of 0.95 years, this investment case is even more profitable. A vertical integration of extrusion and post condensation for an existing waste manager looks like to be very interesting in numbers. The same happened during the upscaling of RPET production, since waste managers had the flakes available they were integrating the consecutive production steps to sell directly the added value to converters. This makes from technical perspective perfectly sense, because sorting is one key knowledge required for proper food contact recycling and waste managers have the biggest experience in it.

3. The third case, which would give zero payback, the constellation is that an existing recycler has all equipment already in an existing building. This is the case of Morssinkhof Sustainable Products, who is today already using post-condensation and extrusion for PET, same as for HDPE that is used further in pallets.

6.5 Market Size

As calculated in chapter 3.3, we estimate the overall EU market for HDPE cap grade of 185.000 tons. Considering that a properly sized line for HDPE recycling has a capacity of 9.125 tons, we would require throughout whole Europe following amount of recycling operators:

$$185.000\ tons\ \div 9.125\ tons = 20{,}27$$
$$185.000\ tons\ \times 2.225\ Euro\ = 411.625.000\ Euro$$

That means we would require at least 21 recycling operators in order to recycle the complete volume HDPE used for cap in whole Europe. With a total 185.000 tons and a possible revenue of 2.225 Euro per ton at 50% premium, this means a market value of more than 400 million Euro.

However, due to the technical limitations described in chapter 5, we consider that only HDPE coming from a DRS would be clean enough as input material to be used in for HDPE cap2cap recycling. Below figure is showing the quantities in the countries where a DRS is available, based on figure 26 and the available quantity of HDPE based on the collection rates exhibited in figure 27. Due to lack of data, Estonia, Lithuania and Croatia are excluded.

Country	Quantity (Millions)	Collection Rate (%)	Total available Closures (Millions)	Quantity HDPE (tons)
Denmark	632	96%	607	1.284
Finnland	456	92%	420	887
Germany	17.078	95%	16.224	34.315
Netherland	1.685	65%	1.095	2.316
Norway	491	88%	432	914
Sweden	836	86%	719	1.521
Slovakia	786	62%	487	1.030
			TOTAL	**42.267**

Figure 62: HDPE from DRS in EU (source: Euromonitor)

This means, realistically we can have 42.267 tons of HDPE available for cap2cap recycling. Which means that with five recycling lines we could cover this entire amount and a total business value of 94 million Euro would be created.

$$42.267\ tons\ \div 9.125\ tons = 4{,}63$$

$$185.000\ tons\ \times 2.225\ Euro\ = 94.044.075\ Euro$$

These 42.267 tons represent 22.85% of the total EU amount of 185.000 tons. This means we could realistically today move to a recycled content of just over 20% in average in all HDPE caps on the EU market. A 100% coverage with today's market situation is in any case not possible, since we would be able to provide rHDPE only in black, red and blue colour, whereas we have several different colours today on the market. To reduce the high impact on cap costs due to increased raw material price there would be possibility to mix the rHDPE grade with virgin material, either to compound already during the extrusion phase or mix directly at the cap producers place in the injection machine.

6.6 Conclusion on Economical Part

It is quite evident that HDPE cap2cap recycling is paying off. Payback is looking very attractive with 2.44 years, even though a ramp up phase is not considered, which surely would delay payback. However, with all sustainability constraints in the plastic packaging industry we can be confident that the ramp up will happen quite fast. The best entry point into HDPE recycling would be to utilize existing assets, like in the case of Morssinkhof Sustainable Products, which is eliminating economical risk of possible start-up issues.

Therefore, other risk can occur that make the business model less attractive, such as:

- A premium over virgin HDPE is required and in tougher times, where consumers and brand owners might want to save money and affordability will be of higher focus than sustainability, they might prefer a cheaper product and virgin HDPE would be of preference
- Energy has a very high impact on product cost and at times of higher energy prices, like we have it now due to sustainability and geopolitical reasons, recycled HDPE could become less profitable
- Another drawback is that with very low virgin prices the margin would shrink or if virgin price would decrease below 750 Euro per ton, it could become not profitable at all
- Recycled material prices are fluctuating in general based on virgin prices, because recycled material price is usually calculated based on a premium applied (between 50-100%). This makes it quite unpredictable how the real profit would look like. Only a certain range can be calculated.

7. Influence of rHDPE on Cap Performance

We know now that HDPE cap2cap recycling is now in better situation in terms of legal aspects with the new regulation released end of 2022, theoretically technically feasible and would be economically viable. However, what is also important is if caps produced with rHDPE grade would perform as required. The general challenges have been described in chapter 5.6, which will be analysed in more depth within this chapter.

The first point to clarify are the requirements coming from brand owners and bottlers. Here we need to differentiate between brand owners with higher brand value like Coca Cola and PepsiCo and products that we see typically at lower price range in the supermarket, which are private label or retail products.

Retail products do not have any general specification and would validate cap performance in a pragmatic way. They would test caps on a bottling line to see if they pass properly the currently installed guides and if the application on the bottle is working well without increasing their scrap rate due to wrongly applied caps. The only parameter they are checking is the opening torque, which represents the force required to open the bottle. A leakage test with bottles lying on the side for couple of days is performed, followed by a storage and transportation test. Afterwards they would approve the caps for purchase if they pass these tests. We can see that these tests are not analytical and do not provide a clear comparison to current performance and therefore are quite limited for judging whether another grade would make it worse or better.

On the other hand, brand owners who produce added value products like Coca Cola and PepsiCo have individual specifications and are among the toughest available on the market. Both specifications of the previously named large brand owners are quite similar and in majority of the cases if a cap is passing Coca cola specification, it will pass PepsiCo specification. Thus, in further analysis we will refer to the Coca Cola specification. Moreover, these are potential customers for a potential rHDPE grade, because they can afford paying more for raw materials that are more sustainable since their beverages are also more expensive, thus providing more margin. These brand owners are also more in the center of discussions when it comes to sustainability due to their large global size and are expected to be pioneers in this field.

When using another material for existing and approved cap designs and production facilities, practically a complete re-approval procedure is necessary covering the below tests:

- Scientific and Regulatory Affairs Material Approval
- Sensory Evaluation
- Dimensional Review
- Application Angle
- Ball Impact Cold
- Bottle Drop Cold
- Opening Performance – Cold and Hot
- Removal Torque – Ambient and Cold
- Proper Application (Secure Seal)
- Strip Torque
- Tamper Evidence

Additionally for Carbonated products:

- Carbonation Retention Elevated
- Carbonation Retention Non-Topload
- TCCC Cycle Test (Standard)
- Topload Vent Test

Additionally for non-carbonated or non-pressurized products:

- Advance TE (still water only)
- Pressure Retention Ambient and Got
- Opening Performance after Reapplication

These are many tests that a cap needs to fulfil before going on a Coca Cola bottle. The reason for such extensive testing is that Coca Cola wants to ensure that consumer will have a safely sealed product that cannot be manipulated and not break immediately when dropped on the floor. In addition, it should not change the taste of the beverage and be convenient in terms of opening, closing and re-opening.

7.1 Coca Cola Testing Criteria

Before getting an understanding how a new material, especially rHDPE, could potentially change the performance of the cap, we will describe shortly the key performance criteria. We will focus only of carbonated products, because the field of application for rHDPE is the largest for CSD applications.

1. Scientific and Regulatory Affairs Material Approval
Purpose: to ensure that materials coming into contact with the product is in compliance with regulatory, sensory and other company specific requirements.
Description: A "Material Composition Request Form" for has to be submitted containing a list of qualitative components of the to be approved material including food law compliance (could be FDA or EFSA approval).

2. Sensory Evaluation
Purpose: evaluate taste compatibility and appearance performance of shells.
Description: 40 litres of product are filled in 300mL bottles. Half of the bottles is capped with a cap of the new material and half of the product is capped with an already approved material. Bottles are stored with touching 50% of the cap for 4 and 10 weeks. After each period sensorial tests are executed and results compared.
For the Appearance Test is executed by shaking the bottle with test and control samples. After six days, resting the beverage surface is analysed for oil slicks, which would be fail criteria.

3. Dimensional Review
Purpose: ensure that cap is produced within specifications of manufacturer.
Description: one full shot (quantity depends on quantity of cavities in the injection mold) are fully measured. Comparison of measured data and specification of the producer is executed.

4. Application Angle
Purpose: application angle out of spec results in possible leakage of the product and/or not proper opening performance

Description: Caps are applied on bottles with application torque as per suppliers' specification and condition for 24 hours at room temperature to allow the package to stabilise after filling. With special equipment, the applied angle of the cap on the bottleneck is measured and compared with suppliers' specification.

5. Ball Impact Cold

Purpose: determine the ability of a cap to withstand impact damages at cold temperatures

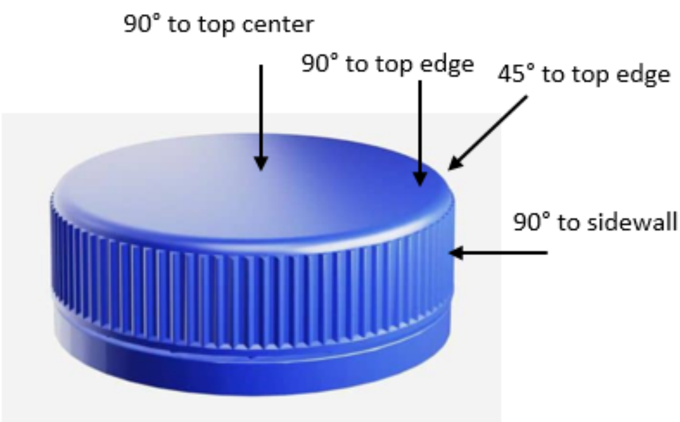


Figure 63: Ball Impact Test

Description: 48 bottles are filled, capped and stored at 4°C for 24 hours. Bottles are then one by one fixed in special equipment, where a specified steel ball is dropped from a height of 559mm surfaces of the cap (see figure 50). Results for damages, cracks or releases are recorded.

6. Bottle Drop Cold

Purpose: Get an understanding if a closure will stay on a bottle when the bottle will be dropped.
Description: 24 bottles to be filled, capped and stored at 4°C for 24 hours. Bottles are dropped from a height of 1.8m in a vertical and horizontal position. Damages are recorded based on cracks, venting and releases.

7. Opening Performance – Cold and Hot

Purpose: Determine the ability of caps to vent gas sufficiently during opening when full or half-full at hot and cold temperatures
Description: 200 bottles are filled, capped and conditioned for 48 hours at 38°C. 100 bottles are filled, capped and conditioned for 48 hours at 4°C. Bottles are then opened in a quick manner and the venting performance is recorded (when gas is released and if it causes release of the closure from bottleneck). Both, hot and cold bottles are t hen conditioned at 22°C for 24 hours. Opened again, half of the product is poured, bottle re-closed and conditioned again at hot and cold temperatures for 24 hours. Opening test is performed again with half filled bottles. Besides checking when closures are released from bottleneck, the performance of the temper evidence band is recorded, e.g. if the band is separated properly, hinging or removed only partially.

8. Removal Torque – Ambient and Cold

Purpose: determine what is the removal torque required for consumers to open the bottle
Description: 156 bottles are filled, capped. 12 bottles are opened within 15 minutes to verify the initial removal torque. Of the remaining bottles, half is stored at 22°C and the other half at 4°C. After 24 hours, 2 and 4 weeks samples are removed and removal torque tested. In addition, the torque to remove the temper evident band is measured.

9. Proper Application (Secure Seal)

Purpose: evaluate integrity of the sealing package

Description: 12 bottles are filled and capped. Upper part of the bottle is cut out and assembled into a special pressure chamber. Pressure is increased with a specified ramp first until 6.9 bar and afterwards until 12 bar. At 6.9bar, the bottle is not allowed to leak. At 12 bar leakages are allowed, but cap has to stay on the neck and not release (strip).

10. Strip Torque

Purpose: stripping resistance of a cap when turned in the wrong direction. If a cap can be stripped too easy, it is a sign that a cap can blow off at regular bottle pressures.

Description: 12 bottles are filled, capped and conditioned for 24 hours at 38°C. Samples are placed into an automatic torque meter, which is rotating the closure at a steady rate in clockwise direction. When the cap jumps (strips), the torque is collected.

11. Tamper Evidence

Purpose: evaluate the ability of closure to resist tampering (possibility to remove the cap without damaging the tamper evidence band). This test is to protect the product from being poisoned in the time between being filled until the consumer drinks it.

Description: 50 caps are sent to Coca Cola Packaging Department. Specialists are trying to remove the cap with special tools without damaging the temper evidence band.

12. Carbonation Retention Elevated

Purpose: determine the ability of a cap to retain carbonation when the bottle is exposed to elevated temperatures

Description: 96 bottles are filled, capped and conditioned at 38°C. The carbonation level is measured after 24 hours, 3, 7 and 14 days.

13. Carbonation Retention Non-Topload

Purpose: determine the ability of a cap to retain carbonation under static conditions at ambient temperatures

Description: 96 bottles are filled, capped and conditioned at 21°C. The carbonation level is measured after 24 hours, 2, 4 and 6 weeks.

14. Carbonation Retention Topload

Purpose: determine the ability of a cap to retain carbonation under topload and elevated temperatures

Description: 96 bottles are filled, capped and conditioned at 40°C. Test intervals are after 24 hours, 2, 4 and 6 weeks. At every test interval, 24 bottles are stored under ambient conditions for 24 hours and then used for test. The samples are placed under 45.5kg topload applied for 7 days. Bottles are stored for another 24 hours after topload removal and carbonation level is measured.

15. TCCC Cycle Test (Standard)

Purpose: Evaluate the ability of a cap to stay on the bottleneck when the package is exposed to repeated cycles of heating and cooling

Description: 36 bottles are filled and capped. For three times the interval of 6 hours at 60°C and 18 hours at 32°C is repeated. At the end of each cycle, the cap needs to be checked for cracks, released, leakers or deformed caps.

16. <u>Topload Vent Test</u>
Purpose: evaluate the ability of a cap to retain pressure under topload at elevated temperatures.
Description: 24 bottles are capped, filled and conditioned for 48 hours. The bottles are placed in a water-filled cylinder. Topload is continuously increased at a certain rate until 45.4kg is applied. It is recorded at which topload gas bubbles would be seen, which is a proof of venting under the closure.

7.2 Possible rHDPE Influence on Cap Performance

A change of the raw material is bringing in any case changes to the cap performance, even if the change is happening between two virgin grades. However, for rHDPE there are additional challenges like purity and consistency in quality in terms of MFI and colour that can bring additional variables to change the behaviour of the cap on the bottle.

The possible affects and by how much probable and critical these influences are on each test are exhibited in below table. It is important to mention that for every test criteria, only the influence on this specific test has been taken into account and not possible influence of one test to the other like a different application angle would lead to a different removal torque due to changed preload on the sealing package.

In addition, the matrix is build considering that no change of the cap design is made, nor any change in steel dimensions of the injection mold. Only a change of the raw material from currently used virgin grade to a possible rHDPE grade.

Testing Criteria	Possible Influence	Probiability	Risk Level	Comment
Scientific and Regulatory Affairs Material Approval	Not allowed to be used if not passed regulatory approval	Low	Low	Regulatory approval is carried out before using recycled plastics in production. Thus, it is not probable that this will have any affect.
Sensory Evaluation	Input material inconsistent	Medium	High	Even if bottles are sourced from DRS, a batch to batch varation can appear. It cannot be assured that consumer did not fill a content into the bottle that is changing sensorical properties
Dimensional Review	- Different molecular strucuture than vigin used - Different MFI - Batch to batch varations	High	Low	Parameters for injection will need to be adapted to get dimensions in specifcation. However, the complexity for production is increasing, because a batch to batch variation is probable and parameters need to be changed more frequently compared to virgin
Application Angle	- Different material brings a different friction between PET and HDPE due to different rigidity of the sealing package - Batch to batch variations	Medium	Medium	Bottlers will need to change settings of their cappers to achieve proper application angle. Due to the different friction the required force to get the cap in specificaiton for the angle will differ. Batch to batch variation is most critical. For every new batch the bottler will need to check the application angle and change settings of capper if required

Ball Impact Cold	- Different material rigidity - Batch to Batch variations	High	High	Softer raw material is better for ball impact performance. If rHDPE would be harder, it means it would become less brittle and change negatievly the ball impact performance. A possible batch to batch variation can bring inconsistency of results over time.
Bottle Drop Cold	- Different material rigidity - Batch to Batch variations	High	High	Same as the Ball Impact Test, this test is verifying the resistance against mechanical impact nad infleunce from used material is consequently high.
Opening Performance – Cold and Hot	- Different material rigidity - Batch to Batch variations	Low	Low	Different friction give the cap less time to vent what can change the result. However, the influence would be rather low. A more significant influence can occur on the temper evidence band performance and create hinging or partial removal. But the risks for a misperformance of the cap are low.
Removal Torque – Ambient and Cold	- Different material rigidity - Batch to Batch variations	High	High	Initial removal torque is primarily determined by the preload of th sealing package and rigidity of raw material. This can be contained by using different amounts of slip agents to balance out the removal torques. Due to different ridigity of raw material the band breaking torque would be also influences sgnficiantly. To allow the consumer to open the bottle conviently, the consisntency over time is important. Batch to batch varations can also here bring the removal torque up that consumers won't be able to open the bottle.
Proper Application (Secure Seal)	- Different material rigidity - Batch to Batch variations	Medium	High	Different rigidity of recycled plastic can deform the cap under high pressure differently and allow it to strip. Stripping represents a high risk that cap could hurt the consumer. But probability that the material will have such a high influnce is not so high, because this feature is highly design dependent
Strip Torque	- Different material rigidity - Batch to Batch variations	Medium	High	Stripping occurs when sidewools deform so much, that the thread would strip. More rigid sidewalls allow better strip torque performance. Risk for consumer is high, because he can be hurt if cap would blow off from the bottle.
Tamper Evidence	- Different material rigidity - Batch to Batch variations	High	High	Raw material has a high impact on the temper evidence performance. A more rigid cap is more difficult to be removed without damaging the temper evidence. This represents als a high risk for the consumer that the beverage could be poisened.

Carbonation Retention Elevated	- Different relaxation due to temperature elevations	High	Medium	Under longterm pressure, the sealing package would deform easier if rigidity is high and allow carbonation to be released faster. Consumer could drink a beverage with a low carbonization content
Carbonation Retention Non-Topload	- None	Low	Low	Non-Topload test depends mainly of the cap design and diffusion of carbonization throug the material. A different material should not change the retention significantly as long the material is HDPE.
Carbonation Retention Topload	- Different material rigidity - Batch to Batch variations	High	Medium	Under topload the cap can deform differently depending on the raw material used and allow gas to escape. Consumer could drink a beverage with a low carbonization content
TCCC Cycle Test (Standard)	- Different material rigidity - Batch to Batch variations	Medium	Medium	The more rigid the raw material is, the lower is the risk that cap will release. Is also highly design specific, depending on the side wall thickness. Thus, influnce would be not high inf only material changes.
Topload Vent Test	- Different material rigidity - Batch to Batch variations	Medium	Medium	With increased rigidity, it is estimated that the vent test should be passed easier. However, is depending more on the cap design and only material change should not change results significantly.

Figure 64: Matrix Cap Performance

7.3 Conclusion on Cap Performance using rHDPE grade

We can clearly conclude that passing the legally set boundaries in terms of chemical quality of rHDPE are by far not the only challenge to introduce rHDPE cap grade on the market. The large brand owners, who are mostly interested in more sustainable solutions because there are the biggest polluters in the consumers head have also the highest interest to move into rHDPE. But they have also the most strict requirements in terms of cap performance, which has a very high complexity related to cap design and raw material combination. It can well be, that a current cap design might not work at all with rHDPE grade.

As shown in Figure 64, the influence on cap performance is very high and can become even dangerous for the consumer if for instance strip torque becomes very low, which is an indicator that a cap can blow off from the bottle and hurt the consumer. On the other hand, proper removal torques allow consumers to conveniently open the bottle and if too high, children or elder people could have difficulties to open the bottle. In both cases, the brand value due to bad packaging performance would be damaged.

Important is also to mention that in the Coca Cola specs nothing is mentioned regarding Environmental Stress Cracking Resistance. Especially CSD caps can due to inside pressure of the bottle crack after a certain period. Longer chains in the molecular structure are support a higher degree of ESCR and this might be also a high risk factor that caps made of rHDPE due to the possible chain cross-linking and scission will crack when bottles will be still on the shelf.

Brand owners will need to be careful in the validation of rHDPE grades and balance properly a possible damage in brand value due to bad packaging performance with the increase of brand value by achieving higher degree of sustainability.

8. Environmental impact

As we learned, HDPE is a fossil-based material, what means that CO2 emissions are generated during its production. In average, we speak about 1,6kg CO2 per kg HDPE (=1,6ton CO2 per ton HDPE) (CHEManager, 2010). The interesting question arise: how much CO2 we would save if we would transition to caps produced out of rHDPE? For this calculation, we make following assumptions:

- CO2 emissions to get raw materials on site are the same for virgin and rHDPE
- Shipment distance to cap production site is the same
- No impact on energy consumption during cap production

That means we look only at the production process of rHDPE. In Figure 47, it was shown 100 kWh/ton for gas consumption and 725 kWh/ton for electricity consumption.

To calculate the CO2 generated for the gas consumption is straight forward, we know that for every kWh we require 200,8g CO2 (=0,2008 kg) (Volker Quaschning und Bernhard Siegel, 2022). We multiply the 0,2008 kg/kWh with 100 kWh that equals 20,08kg, which represents the amount for one ton HDPE.

For generating electricity different sources of energy are used (nuclear, sustainable and fossil based). Below figure is showing the average CO2 emissions per kWh for the last years, for our calculation we take the 2021 value of 275g CO2 (=0,275kg) per kWh.

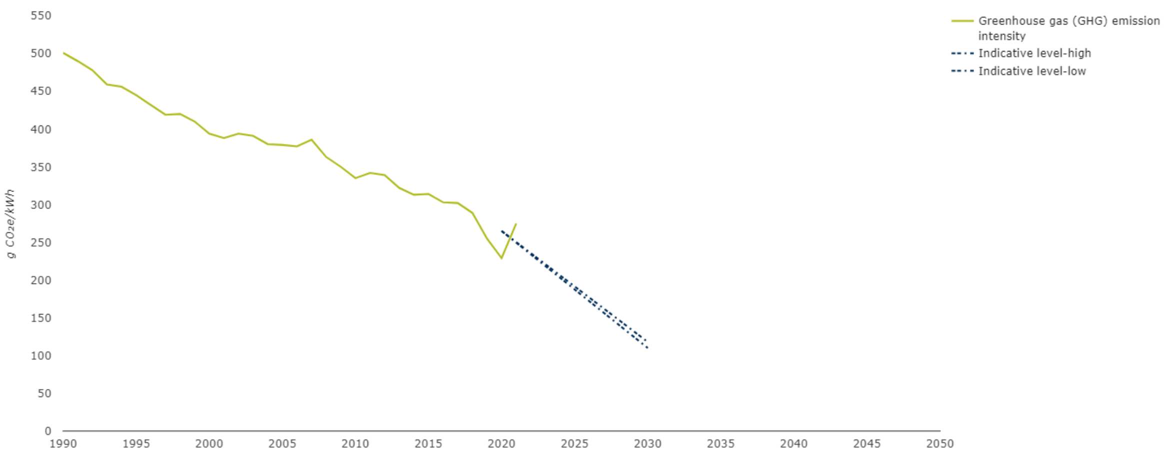


Figure 65: Green House Gas Emissions for electricity generation (European Environment Agency, 2022)

We multiply the 0,275 kg CO2/kWh with 725 kWh/ton, which equals 199,375 kg CO2 per ton of HDPE. In total, gas (20,08kg) and electricity (199.375kg) together have 219,455 kg CO2 (~220 kg CO2) to recycle one ton of HDPE. 220kg is only 13,75% of the CO2 required to produce virgin HDPE or a saving of 1.380 kg CO2 per ton HDPE, means 86,25% savings. This calculation is very similar to the claim of plastic part manufacturer and recycler Alpla, who is advertising CO2 savings up to 88% for HDPE recycling (Poole, 2022).

To get an understanding of the total savings, we will analyse the total CO2 savings for two cases, where a DRS is already in place with current collection rates and a hypothetical best case that DRS would be implemented in all EU countries at average collection rate of 90%.

1. Current available volume in countries with DRS available

In chapter 6.5 we calculated based on individual collection rates in countries with existing DRS that the total available amount for cap recycling is 42.267 tons. Multiplied with the saving 1,38 tons CO_2 we arrive at 58.328,46 tons CO_2 savings possible already today.

2. Hypothetical case – all EU countries with DRS at 90% collection

In chapter 3.3 we calculated based on some assumptions that the total HDPE consumption for caps in Europe is 185.000 tons. At a collection rate of 90%, we will have 166.500 tons for recycling available. We multiply these with 1,38 tons CO_2 and get 229.770 tons of CO_2 savings per year, if we would utilize all HDPE collected on EU market.

To get a better understanding of these numbers, we make a comparison. A typical passenger vehicle emits about 4,6 tons of CO_2 per year (EPA, 2018). For the first case, this means we save what 12.680 cars would emit per year. For the second "best" case, the savings are equivalent to the emission of 49.950 cars, which is quite significant saving.

9. Conclusion

Plastics are bringing a huge contribution to our life. Especially when we speak about food and beverage packaging, they provide a light and safe solution. However, the more we produce the more waste is generated and becomes more critical for the environment. The resolution to get rid of this waste, re-use it and consequently reduce the CO2 footprint of our packaging, recycling is a crucial tool. The challenge here is multidimensional, consisting of legal, technical and economic factors. Especially when it comes to food contact compliant plastics like HDPE caps, the safety of the consumer is critical because the beverage is in direct contact with the cap and contamination is likeable. Even though, there are already technologies in pace that are allowed for usage for food contact recycling of HDPE in th US, but these are holding a FDA approval, which is easier to obtain than a positive EFSA opinion that is required in the European Union.

Without proper legislation, the safety of consumer cannot be guaranteed. The challenge lies in understanding what really means safe and how to validate it. On the recycling of PET, there is huge data available, also because the amount of PET on the market is huge, which represents a big market and recyclers were ready to invest in the validation, because the risk-reward ratio was larger. For HDPE caps2caps recycling, this is not the case. The weight of a cap relatively small compared to a PET bottle, what is reducing the mass of HDPE caps on the market compared to PET, thus reducing the interest to risk validating over years a possible technology and possibly failing. The EFSA was here the main driver to hold approvals for possible technologies due to availability of scientific data. However, there was also no legislation available on the validation of new technologies, which would lead to clearly processes and take the responsibility from the EFSA to give a positive opinion based on very little data. Here the new regulation 2022/1616 is providing clear guidelines with introducing the definition of “novel technologies”. It is defined that recyclers can go into production with a novel technology that has no positive EFSA opinion yet, provided that all batches are controlled to be compliant with regulation 10/2011 for material safety and produced following the GMP. After showing consistency in the process and safe output for a longer period, the application for EFSA opinion is executed and followed by a positive opinion the novel technology becomes a “suitable technology”. Compared to previous legislation, this new process is a breakthrough for entrepreneurs to go into business. After a short period, they can start-up the recycling lines and sell their recycled plastics, which is reducing the risk of putting a system in place and wait for EFSA opinion before starting commercial activities and paying back their investment. Within the validation period due to extensive testing, they get themselves a good understanding of their own technology and how to run it properly with a stable process, reducing the risk of failing on the EFSA opinion. This new regulation is allowing gathering large amount of scientific data, which is allowing the EFSA to give an opinion at all, what was not possible with the old process.

It is not on purpose that the EFSA was holding back positive opinions for HDPE food contact recycling. The technical challenges are severe. Starting with the origin of the collected HDPE that can come from deposit return systems providing waste with low contamination, kerbside collection with little control over contamination and from general waste collection where HDPE can in contact with all kind of waste increasing the possible contamination to the highest. To avoid higher complexity, it is highly recommended to start new recycling technologies in the easiest application field, in our case it would be bottles coming from the DRS. HDPE input material would be already available, because bottles are in majority of the cases given back together with the cap. After being crushed into flakes, HDPE and PET are divided in the today’s set-up recycling process by sink-float technology. That means in the new HDPE decontamination technology we consider these flakes as input material. Technically, there are three main issues on mechanical recycling HDPE caps2caps:

1. Input HDPE flakes are of different colours and mixing them all together gives an undefined outcome. Through utilization of NIR sorting technology, there is a possibility to sort up to a certain content by colour, but this makes the rHDPE very expensive. Thus, the strategy should be to concentrate on some chosen colours like blue, red and back. The latter one is the easiest to realize, because black masterbatch can turn a mix of colours into black.
2. The mix of different HDPE input materials is giving as output a material with unknown properties. Cap designs can be adapted to these, but it is questionable if the properties of output will be stable from batch to batch due to possible variation of input material.
3. Decontamination of HDPE is by far more difficult than PET. One reason is the low melting point of HDPE that does not allow running higher temperatures in solid state and allow VOCs to be extracted easier. On the other hand, the chemical structure of HDPE is set-up that enclosed VOCs are in general more difficult to extract.

On the economic side, we can conclude that this business is capex intensive, thus requires commitments from brand owners before going for the full investment to reduce risk. There are two concerns related to profitability, firstly the high energy costs. Especially in today’s times, where energy is fluctuating heavily it could have a direct impact on profitability of this business. Secondly, rHDPE is related to virgin prices, because at low virgin prices and very high rHDPE prices brand owners most likely would tend for savings with low virgin prices rather than seeing the benefit of selling more having a more sustainable image. As a breakeven point when rHDPE is profitable, we calculated just below 750 Euro per ton as virgin price. Anything below will justify the high conversion cost from non-food HDPE to food contact compliant HDPE. When considering a new facility, the calculation shows a payback around 2.5 years. However, due to the limited market and the fact that access to input HDPE from DRS is limited, we would assume that an installation into an existing recycling facility is more likely. With vertical integration the investment is lower due to existing assets installed, thus payback at full utilization is around one year.

Besides having a “clean” rHDPE source, brand owners want their package to be safe and consumer friendly. High value brands have strict requirements towards cap performance and a large list of specifications to be fulfilled. While many factors depend on cap design, the choice of the suitable raw material plays also a big role. A change in raw material can easily affect the performance and make the cap leak or difficult to open, what would a negative impact on the brand value of bottlers. The analysis is showing that the different properties of a possible rHDPE, but also the consistency of these properties would change cap performance so much, that specific tests of brand owners would not pass and consequently they would refuse using these rHDPE grades. A case-by-case trial of rHDPE grade in combination with specific cap designs would be required in order to understand suitability and obtain brand owners approval.

We can see that it is not straightforward with introducing rHDPE grades. However, many specific challenges could be eliminated if the market would shift towards a recyclable cap, which means design the cap for recycling.

1. The first step would be to eliminate individual marketing with special colours and go ahead with a clear cap without additives. This would avoid lots of complexity from different colours.

2. Furthermore, the usage of virgin grades with specific properties should be introduced. This would remove from the possible fluctuations of material properties and allow more usage of rHDPE grades.

The environmental impact of saving CO2 by using rHDPE instead of virgin HDPE is quite significant, considering that we speak about low weight if 2g caps on bottles. Besides avoiding littering in the environment the CO2 savings represents one more strong argument for HDPE cap2cap recycling.

As part of this Thesis, it was planned that Morssinkhof Sustainable Plastics would produce some sample grades of rHDPE, which should have been injected into caps at Corvaglia. Corvaglia would then make the full cap performance validation. However, due to production constraints at Morssinkhof, this could not be executed on time and will be performed later.

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