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Impacts of collection and treatment of dry recyclables

Commingling practices and their environmental and socio-economic impacts

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Contents

Abstract

This study focuses on the separation, collection and subsequent management of the dry recyclables (i.e. beverage cartons, glass, metal, paper and cardboard, and plastic) of Municipal Solid Waste in the EU27. The goal of the study is to recommend compliant/noncompliant and in general best commingling practices for separate collection of dry recyclables in view of the obligations required by the EU Waste Framework Directive and its upcoming revision. To this purpose, the study first identifies the most relevant collection and commingling practices for dry recyclables around the EU27 and subsequently assesses the environmental and socio-economic impacts of fifty-five different management practices in view of providing evidence-based recommendations for the revision of the EU Waste Framework Directive, with special focus on the derogations from a strict separate collection of the recyclables. The results indicate that single-stream collection (commingling all dry recyclable together) clearly incurs detrimental environmental, economic, and socio-economic effects and should be avoided. Similar conclusions apply to 2-stream systems, although the environmental performance gap with 3- and 4-stream systems is less pronounced and their socio-economic costs are comparable. Systems with 3- or 4-stream achieve similar environmental and socio-economic performances and are recommended. There is no evidence that 4-stream systems are better than 3-stream systems, suggesting that some degree of commingling can be safely accepted and/or even recommended.

Acknowledgements

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Executive summary

Policy context

Directive 2008/98/EC (Waste Framework Directive), as amended by Directive 2018/851/EC (art. 10), mandates that waste shall be subject to separate collection[1] and shall not be mixed with other waste or other materials with different properties. However, Member States may allow derogations from this provision provided that some conditions are met. These conditions relate to: i) demonstrating that collecting certain types of waste together does not affect their potential to undergo preparing for re-use, recycling or other recovery; ii) separate collection does not deliver the best environmental outcome when considering the overall environmental impacts of the management of the relevant waste streams; iii) separate collection is not technically feasible taking into consideration good practices in waste collection; iv) separate collection would entail disproportionate economic costs.

Within this study, we examined the current status of the implementation of separate collection for the main 'dry recyclables' (glass, plastic, beverage carton, paper and cardboard, and metal waste) across the EU27. From such analysis it is evident that in the vast majority of the cases a separate collection of each individual material constituting the dry recyclables is *not* enforced; instead, some form of commingling is always in place, which formally represents a derogation from the provisions of the Waste Framework Directive. This occurs for many reasons, mainly owing to the techno-economic constraints related to separating individual materials (with low share and weight on the total; e.g. metal), but also simply to poor collection practices.

[1] 'Separate collection' means the collection where a waste stream is kept separately by type and nature so as to facilitate a specific treatment.

Key conclusions

The evidence obtained via life cycle assessment and costing performed on fifty-five management scenarios, reflecting the main variations of commingling systems for dry recyclables across the EU, indicates that:

- Systems with a degree of separation of 3 streams or 4 streams perform significantly better than systems with a lower degree of separation (or higher degree of commingling; i.e. single- or dual-stream systems) environmentally.
- There is no clear evidence that 4-stream systems perform better than 3-stream systems, neither environmentally nor economically. This tells that such degree of commingling is acceptable and does not seem to lead to detrimental environmental and socio-economic effects compared to systems with a higher degree of separation.
- Single-stream collection (1-stream) of dry recyclables achieves the worst environmental performance across all the impact categories considered in the assessment, followed by dual-stream (2-stream) systems. This holds true even when accompanied by deposit-refund-scheme (DRS) on selected material fractions such as glass bottles, metal cans, and PET bottles.
- Single-stream collection (1-stream) of dry recyclables achieves the worst economic performance (conventional costs) and the worst socio-economic performance (societal costs). This is due to the reduction of secondary material recovery relative to systems with a higher degree of separation (or less commingling). This holds true even when they are accompanied by deposit-refund-scheme (DRS) on selected material fractions such as glass bottles, metal cans, and PET bottles.
- Systems with 3- and 4-stream incur higher collection, sorting and transport conventional costs but overall less total conventional costs at a system-wide level relative to single-stream systems, thanks to the revenues from secondary materials. The same applies to the total societal costs. Instead, when compared against dual-stream systems, the ranking is not as neat because dual-stream have competitive costs and the environmental performance gap is not as pronounced as for single-stream.
- Sorting systems on the mixed residual waste are complementary to separate collection and can even improve the overall waste management system performance under prerequisites such as separate collection of bio-waste, paper and cardboard, and metal/glass drinks containers (i.e. under already advanced separate collection systems).
- Generally, the higher the recycling rate, the lower the net Climate Change impact of the waste management system.
- Commingling of glass with plastic waste, especially flexible, is not a recommendable practice in general because of the contamination of the plastic streams with glass fines and dust.

Related and future JRC work

This study is part of a larger project namely Circular Economy Action Plan I (CEAP Administrative Agreement I between JRC and DG ENV) that contains a number of work packages related to the impact assessment of sewage sludge management, proposals for end-of-waste criteria for a set of waste materials, assessment of the definition of recycling, battery waste recycling and separate collection of waste (of which this study belongs). In relation to the latter, additional outputs are foreseen in particular on waste bin labelling harmonisation and quality management systems.

Quick guide

This report starts with a general policy background (section 2) and a description of the collection practices in place across the EU27 (section 3). This is followed by the description of the assessment methodology applied and results (section 4). The final recommendations are presented in section 5.

1 Introduction

Policy context

Directive 2008/98/EC, as amended by Directive 2018/851/EC, and commonly known as the 'EU Waste Framework Directive' (WFD) regulates the management of waste across EU members. The directive, in its Article 10, states that waste *shall be subject to separate collection*[2] *and shall not be mixed with other waste or other materials with different properties*. However, Member States may allow derogations from this provision provided that some conditions are met. These conditions relate to: i) demonstrating that collecting certain types of waste together does not affect their potential to undergo preparing for re-use, recycling or other recovery; ii) separate collection does not deliver the best environmental outcome when considering the overall environmental impacts of the management of the relevant waste streams; iii) separate collection is not technically feasible taking into consideration good practices in waste collection; iv) separate collection would entail disproportionate economic costs.

Problem addressed

Having in mind the prescriptions of the WFD in terms of separate waste collection, a number of techno-scientific studies and preliminary evidence from EU monitoring exercises (such as the Early Warning Assessments by the EEA) seem to indicate that in the vast majority of the cases a separate collection of each individual material constituting the dry recyclables is not actually enforced; instead, some form of commingling is in place, which formally represents a derogation from the provisions of the EU Waste Framework Directive. This occurs for many reasons, mainly owing to the techno-economic constraints related to separating individual materials but also simply to poor collection practices.

Purpose of this report

JRC has undertaken this study on behalf of DG ENV to assess the current status of dry recyclables separate collection (*alias* of their commingling practices) across the EU and their environmental and socio-economic implications. The study is part of an Administrative Agreement with DG ENV, namely CEAPAA1. The overarching goal of the study is to recommend compliant and noncompliant practices in view of the EU obligations for separate collection of the dry recyclables contained in MSW. To fulfil this goal, the study first identifies the most relevant collection practices for dry recyclables across the EU27 and subsequently assesses the environmental and economic impacts of such practices in view of providing evidence-based recommendations. To assess the impacts, the full life cycle of the waste is taken into account, including not only collection but also all the downstream operations involved in the management (such as transport, sorting, recycling and any other treatment) up until final recovery or disposal of the waste that was once generated.

The conclusions and recommendations from this study can be used in the context of the revision of the EU Waste Framework Directive, notably with respect to Article 10, to provide further prescription or simple guidance for the separate collection of dry recyclables present in MSW.

[2] 'Separate collection' means the collection where a waste stream is kept separately by type and nature so as to facilitate a specific treatment.

2 Background: Definitions and policy context

2.1 Notions and definitions based on the EU Waste Framework Directive

Article 10 of Directive 2008/98/EC (Waste Framework Directive; European Commission, 2008), as amended in Directive 2018/851/EC (European Commission, 2018), provides the following definitions, useful in the context of this study:

"**Municipal waste**" means: (a) mixed waste and separately collected waste from households, including paper and cardboard, glass, metals, plastics, bio-waste, wood, textiles, packaging, waste electrical and electronic equipment, waste batteries and accumulators, and bulky waste, including mattresses and furniture; (b) mixed waste and separately collected waste from other sources, where such waste is similar in nature and composition to waste from households;

Municipal waste does not include waste from production, agriculture, forestry, fishing, septic tanks and sewage network and treatment, including sewage sludge, end-of-life vehicles or construction and demolition waste. This definition is without prejudice to the allocation of responsibilities for waste management between public and private actors; this means that the municipal waste is defined and reported as such regardless of whom is collecting such waste. From now onwards this will be abbreviated as MSW (Municipal Solid Waste).

'**Bio-waste**' means biodegradable garden and park waste, food and kitchen waste from households, offices, restaurants, wholesale, canteens, caterers and retail premises and comparable waste from food processing plants.

'**Separate collection**' means the collection where a waste stream is kept separately by type and nature so as to facilitate a specific treatment.

'**Re-use**' means any operation by which products or components that are not waste are used again for the same purpose for which they were conceived.

'**Treatment**' means recovery or disposal operations, including preparation prior to recovery or disposal.

'**Recovery**' means any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy. Annex II of Directive 2008/98/EC on waste sets out a non-exhaustive list of recovery operations.

'**Material recovery**' means any recovery operation, other than energy recovery and the reprocessing into materials that are to be used as fuels or other means to generate energy. It includes, inter alia, preparing for re-use, recycling and backfilling.

'**Preparing for re-use**' means checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be re-used without any other pre-processing. For example, the preparation on furniture, objects, books, clothes, electric and electronic devices (by means of repairing or refurbishing operations) prior to their reintroduction on the market.

'**Recycling**' means any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations.

'**Backfilling**' means any recovery operation where suitable non-hazardous waste is used for purposes of reclamation in excavated areas or for engineering purposes in landscaping. Waste used for backfilling must substitute non-waste materials, be suitable for the aforementioned purposes, and be limited to the amount strictly necessary to achieve those purposes.

'**Disposal**' means any operation which is not recovery even where the operation has as a secondary consequence the reclamation of substances or energy.

2.2 Other technical notions and definitions used in this study

Additional to the definitions taken from the EU legislation on waste, the following key terms and definitions apply in this study:

'**Capture rate**': Quotient of mass between the quantity of waste separated at source (including impurities that are unintendedly ending up with it) and the quantity of the same waste generated (%) (e.g., glass waste separately collected over total glass waste generated).

'**Commingling**': Commingling means the collection of two or more waste streams (e.g., plastic and metals) in a single container and does not impede high-quality recycling or other recovery of waste, in line with the waste hierarchy (EU Directive 2018/851).

'**Degree of separation**': The clustering of the scenarios based on the number of streams for recyclables (e.g. mono-stream, dual-stream, etc.). This is also known as 'Degree of commingling'.

'**Dry recyclables**': Generic term for the waste streams paper and cardboard, glass, metals, plastic, beverage cartons.

'**Dual-stream collection (or twin-stream, or 2-stream)**': Here intended as dividing dry recyclables in two separate streams, generally one rich in fibre and one rich in containers-like materials.

'**Impurities (also known as misplacement, misthrow, contaminant, and cross-contamination)**': Waste that is not targeted for separate or commingled collection by local authorities in charge of waste management, or waste management companies[3].

'**Mono-stream collection**': Here meant as separate collection of the dry recyclables by nature and type, strictly in line with the WFD.

'**Impurity rate**': It is defined as 100% minus purity rate; it represents the % of non-target material in a given waste stream (e.g. percent of non-glass in a glass waste stream).

'Purity rate': The percentage of *target material* in a given waste stream,

'Recycling rate': A quotient of mass between the output stream from a recycling plant (secondary raw material, e.g., recycled PET flakes/pellets/granules originating from waste, including market-acceptable impurities) and the total mass of waste material generated (%).

$$\frac{\substack{Output\ from\ a\ reycling\ plant\ originating\ from\ \ waste \\ incl.\ market\ acceptable\ impurities\ \ (ww)}}{Mass\ of\ \ generated\ waste\ (ww)}\ \%\ (Eq.1)$$

'Residual waste' (also known as mixed residual waste or mixed waste): The stream of municipal solid waste which is composed of all material fractions either not targeted by the separate collection scheme in place or not captured by it because of the efficiency of the source segregation by citizens or other municipal waste producers.

'**Single-stream collection (or 1-stream)**': Here intended as the practice of commingling all dry recyclables in one single stream.

'Sorting rate': A quotient of mass between the output stream from a MRF (i.e., the wet weight of the bale of the target recyclable, e.g., PET) and the stream of the separately collected waste stream in input to the plant (Eq. 2). While other definitions of sorting rate have been suggested (see Cimpan et al., 2015; Mastellone et al., 2017), we here apply Eq. 2 as it reflects parameters typically known by the plant operators and widely used in the sector.

$$\frac{Bale\ of\ target\ waste\ material\ (ww)}{Input\ of\ target\ waste\ material\ to\ the\ plant\ (ww)}\ \%\ (Eq.2)$$

'**Target material**': The waste or mix of waste that is the objective target for separate or commingled collection defined by local authorities in charge of waste management, or waste management companies. Depending on the objectives of the waste collection system, a certain waste is targeted as it is sortable and recyclable and a market exists for the final secondary raw materials.

[3] We are aware that in some cases sorting plants run by Producer Responsibility Organization (PRO) consider as impurities non-packaging material (e.g. non-packaging plastic) which is collected by municipalities as part of the (packaging) stream. In this study, non-packaging material that ends-up in the associated stream (e.g. non-packaging plastic ending up in the plastic stream) is not considered impurity because, at a system-wide level, the material can be (and in many cases will be) recovered and recycled.

Notice that other terms and acronyms typical of the waste management terminology are used throughout this document. A full list of abbreviations and definitions may be found in the section 'List of abbreviations and definitions' at the end of this document.

2.3 Policy background: Separate waste collection and conditions for derogation

Directive 2008/98/EC (Waste Framework Directive), as amended by Directive 2018/851/EC, states that (Paragraph 1, Art. 10) 'Member States shall take the necessary measures to ensure that waste undergoes preparing for re-use, recycling or other recovery operations…'. Paragraph 2, Art. 10 states that 'Where necessary to comply with such obligations [that of paragraph 1, Art. 10] and to facilitate or improve preparing for re-use, recycling and other recovery operations, **waste shall be subject to separate collection**[4] **and shall not be mixed with other waste or other materials with different properties'**. However, Member States may allow **derogations** from this provision provided that at least one of the following conditions is met:

- **collecting certain types of waste together does not affect their potential to undergo preparing for re-use, recycling or other recovery** operations in accordance with Article 4 and results in output from those operations which is of comparable quality to that achieved through separate collection;
- **separate collection does not deliver the best environmental outcome** when considering the overall environmental impacts of the management of the relevant waste streams;
- **separate collection is not technically feasible** taking into consideration good practices in waste collection;
- **separate collection would entail disproportionate economic costs** taking into account the costs of adverse environmental and health impacts of mixed waste collection and treatment, the potential for efficiency improvements in waste collection and treatment, revenues from sales of secondary raw materials as well as the application of the polluter-pays principle and extended producer responsibility.

Art. 10, as amended by Directive 2018/851/EC, further recites that MS shall regularly review derogations under this paragraph taking into account good practices in separate collection of waste and other developments in waste management.

Upon reading Paragraph 2, Art. 10 of Directive 2008/98/EC (Waste Framework Directive) as amended in Directive 2018/851, it appears clear that the legislator intends separate collection as a single-stream collection of individual waste material fractions. In other words, commingling does not appear to be contemplated as separate collection, in any of its multiple forms. However, some degree of commingling is practiced almost everywhere across the EU owing to the techno-economic constraints associated with the separate collection of some materials. A clear case is that of metals, which with a low overall share in the MSW along with their low specific weight would incur disproportionate economic costs for their individual collection and sorting. Further, separation of metals from other materials is relatively easy via commonly established technologies such as magnets for ferrous metals and Eddy Current System separators for non-ferrous metals, which technically justifies their commingling with other selected waste material fractions.

Within this study, we examine the current status of the implementation of dry recyclables separate collection across the EU27. From such analysis it is evident that in the vast majority of the cases a separate collection of each individual material constituting the dry recyclables is not enforced; instead, some form of commingling is always in place, which formally represents a derogation from paragraph 2, Art. 10. The state-of-play of the commingling practices across the EU27 MS is illustrated in section 3.

[4] 'Separate collection' means the collection where a waste stream is kept separately by type and nature so as to facilitate a specific treatment.

3 Current practice in dry recyclables collection

3.1 Overview of general practices in place across the EU

Collection schemes for dry recyclables vary across Member States. The differences encountered are not just at Member State level, but even within the same country the schemes might vary from one municipality to another. Indeed, waste collection schemes are influenced by a series of internal (e.g. waste generation per capita, local waste legislations, etc.) and external (i.e. geographical, socio-demographic, and economic) factors that need to be taken into account when designing them (Joint Research Centre of the European Commission, 2023)[5]. This eventually results in having collection schemes that are location-specific and, therefore, it is rather challenging to define an average collection scheme for dry recyclables at country or even regional level.

In 2021-2022, the European Environment Agency (EEA) developed early warning assessments for all Member States to be fed into Early Warning Reports (EWRs) related to the 2025 recycling targets for municipal and packaging waste. The assessment performed by the EEA envisaged a survey filled out by Member States to have a clear state-of-play on economic instruments used, legal instruments, etc., but also provided a qualitative overview of the collection schemes in place indicating what are the dominant ones for different waste streams accounting also for the urbanization level (i.e. cities, towns and suburbs, and rural areas) and the collection systems (either door-to-door, bring collection points, and civic amenity sites) that affect capture rates and the quality of the collected waste. Based on the qualitative information provided in the Early Warning assessments, we attempted to quantitatively estimate the coverage of single stream and commingling collection schemes per Member State and waste stream (specifically, paper and cardboard waste, glass waste, metal waste, plastic waste, and beverage cartons waste), and we also identified a set of the most common commingling systems that are as follow:

- Plastic, metal, beverage cartons;
- Paper and cardboard, plastic, metal, beverage cartons;
- Metal, plastic;
- Paper and cardboard, glass, metal, plastic;
- Paper and cardboard, beverage cartons.

Our estimation at EU level thus excluded other commingling setups that might exist at Member State level, such as i) glass, metal; ii) plastic, beverage cartons; iii) glass, metal, plastic; iv) paper and cardboard, plastic, metal. Further, from the analysis conducted, it appears that either beverage cartons are commingled with another waste stream or are directly disposed of with the residual waste, but not collected on their own. Finally, the analysis of the EEA's Early Warning assessments also looked into the deployment of Deposit Refund Systems (DRS), whether it is on a voluntary/mandatory base and on what materials is implemented (e.g. glass bottles, plastic bottles). By combining the information provided in the Early Warning assessments and the country-specific reports of FEVE, it was possible to further identify what countries currently have a DRS in place, on what materials, and its coverage. Specifically, the countries identified having an established DRS are Sweden, Finland, Estonia, Lithuania, Denmark, the Netherlands, Germany, and Croatia. The details of such analysis may be consulted in (Albizzati et al., 2023).

3.2 Further process steps and ultimate fate of collected fractions

The collected waste follows different routes for subsequent sorting and recovery depending on the management scheme in place. Typically, after collection at households and commercial services, dry recyclables are sent to appropriate sorting plants (sometimes referred to as 'material recovery facilities', MRF, or selection plants) where bales of targeted material fractions are produced. Such sorting stage is often composed of a series of plants (or lines in the same plant), which here for simplicity of modelling and writing we will group into the so-called 'sorting stage'. Typically, the company in charge of the collection on behalf of a cluster of municipalities delivers the collected commingled waste stream (e.g. plastic, beverage carton, and

[5] Development of an EU harmonized model for separate municipal waste collection and related policy support - D3.1 Literature based analysis report. Deliverable 3.1 of the CEAP AA (Work Package 3 – Separate Waste Collection). (Pending publication)

metal waste) to a first selection plant that separates the commingled waste stream (multi-material stream) into individual waste streams (e.g. one stream for plastic waste, one for beverage carton waste, one for ferrous and one for aluminium waste) while removing impurities to the level required by the subsequent plant or user. Some of these individual streams, notably the plastic waste stream, are compacted, baled and sent to a further sorting plant (or line in the same facility) for further sorting (notably, the plastic waste bale is sorted into bales of individual polymers, e.g. a bale of PET, HDPE, PS).These bales are then sent to appropriate recycling plants for production of secondary material, which quality is often dependent upon the success of the collection scheme in place.

Depending upon the success rate of the source separation by households and commercial services, a share of the generated recyclables ends up in the mixed residual waste (in literature referred often to as 'mixed waste', 'residual waste' or 'residue') that is ultimately disposed of in landfills or incinerated for energy recovery. In some cases, the mixed residual waste undergoes further treatment in the form of an advanced sorting plant to recover additional materials, or, when bio-waste separate collection is poor, mechanical-biological treatment (MBT) to stabilise the organic waste present in the mixed waste prior to subsequent landfilling or incineration while recovering additional recyclables. This is often the case when the mixed residual waste contains a significant share of organic waste (notice that even though a separate collection of organic waste is in place, organic waste is still present in the mixed residual waste due to inefficiencies in source separation). Figure 1 illustrates a typical management scheme for dry recyclables where commingling of selected materials is performed. In the example, material A and E are collected separately, i.e. individually, while B, C, D are commingled. Downstream operations involve sorting and recycling. The non-captured dry recyclables are collected together with the (mixed) residual waste and sent to further treatment. This can be via centralised sorting or MBT[6] (Figure 1a; Figure 1) or direct incineration/landfilling (b; Figure 1). From the mixed waste sorting, a part of the output may further undergo recycling (c; Figure 1) and a part will be destined to landfilling or incineration (d; Figure 1).

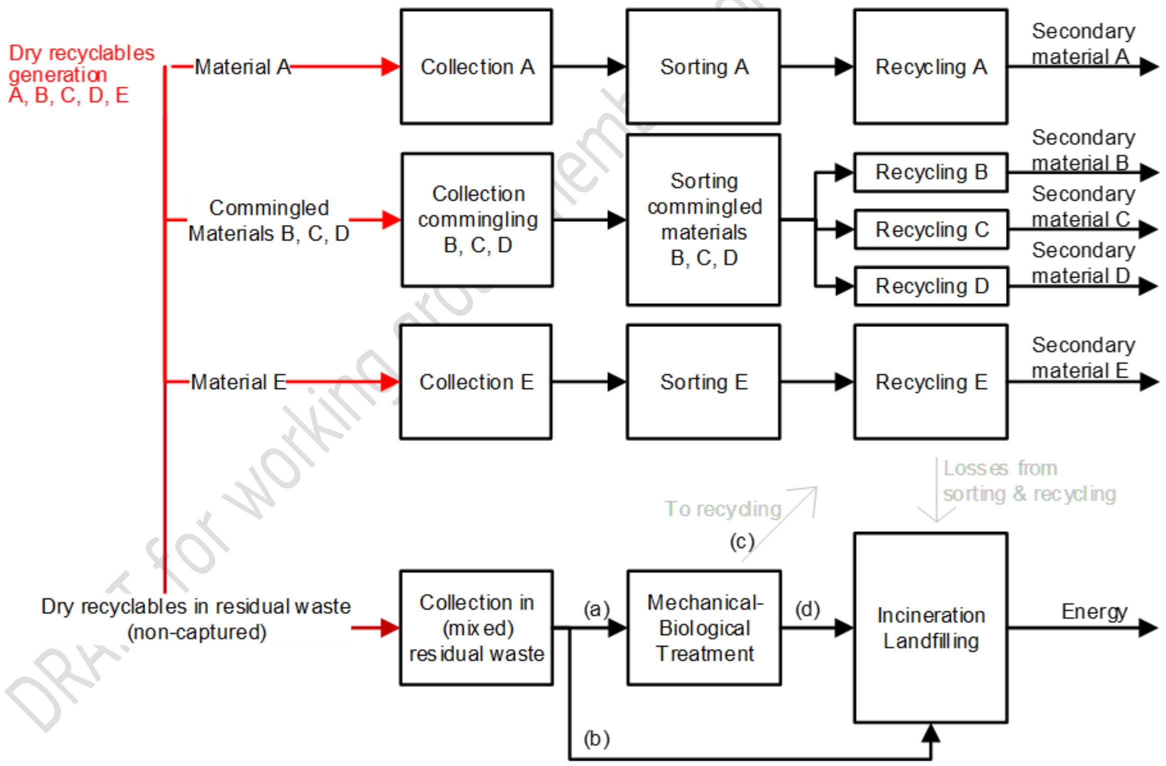


Figure 1. Exemplary illustration of a typical waste management scheme for management of dry recyclables. In this example, material A and E are collected separately, i.e. individually, while B, C,

[6] We distinguish in the terminology between a centralised sorting plant aiming to recover targeted materials (e.g. plastic and metals) from a relatively clean residual waste fraction and a MBT plant aiming to primarily stabilise the organic fraction still present in the residual mixed waste due to poor separate collection practices. However, both cases may be seen from a modelling perspective as an additional "centralised sorting stage of the mixed residual waste".

D are commingled. Downstream operations involve sorting and recycling. The non-captured dry recyclables are collected together with the (mixed) residual waste and sent to further treatment. This can be via centralised sorting or MBT (a) or direct incineration/landfilling (b). From the mixed waste sorting, a part of the output may further undergo recycling (c) and a part will be destined to landfilling or incineration (d).

3.2.1 Sorting of dry recyclables (material recovery facilities)

Sorting plants (or Material Recovery Facilities; MRF) can be configured with different equipment and machines depending on the composition of the input-waste to be managed. This is very much dependent upon the collection system in place. According with the state-of-the-art summarised in (Cimpan et al., 2015), the main configurations are as follows:

- Sorting plants for **single-stream commingled** waste, i.e. for a collection system where dry recyclables are collected in a single-stream (i.e. 1-bin).
- Sorting plants for **dual-stream (or twin-stream) commingled** waste, i.e. for a collection system where dry recyclables are divided in two streams (2-bin): i) paper and cardboard (fibre-rich) and ii) plastic, metal, beverage cartons, and glass (container-rich). The sorting plant is equipped with one line dedicated to the fibre-rich and one for the container-rich stream.
- Sorting plants for **lightweight packaging waste**, i.e. for a collection system where dry recyclables are divided into three streams (3-bin): i) paper and cardboard (fibres), ii) glass, and iii) lightweight materials (rigid and flexible plastic, metals, beverage cartons). These should clearly be accompanied by sorting plants (or lines) dedicated specifically to the mono-material streams of glass and paper/cardboard.

It should be kept in mind that other variations from these archetypes occur, dependent on the type of collection scheme in place. For example, in the dual-stream commingled collection flexible plastic (e.g. foils) may go with paper and cardboard instead of with the containers stream. In some countries, beverage cartons are sent to the residual waste in place of being commingled with other containers (e.g. in Denmark up to recent years). A description follows of a single-stream and a lightweight packaging sorting plant based on the work of (Cimpan et al., 2015).

3.2.1.1 Sorting plant for single-stream commingled dry recyclables

A single-stream sorting plant treats a commingled flow composed of the five typical dry recyclable fractions (metal, glass, paper and cardboard, plastic, beverage cartons) and it is typically equipped as in Figure 2 (the Ford MRF in West Sussex UK; figure and relative description taken from Cimpan et al., 2015). This configuration is typical in UK, US as well as in some regions of the EU27 (e.g. Greece and Ireland). The collected recyclables are unloaded from trucks on the receiving area. The process starts with bag opening to release materials. The drum feeder then distributes material to the first conveyor belt leading to a manual sort where large items and materials unwanted for the downstream equipment (e.g., wire) are removed for disposal.

After manual pre-sorting, the primary separation process is performed in a drum screen (trommel). The objective is to pre-concentrate materials and also to break any glass into smaller pieces. The first section, with a cut-off of 75mm, separates the "fines", which contain most of the broken glass material. The second section, with a cut-off of 160x170mm, separates a mixed stream of paper and containers, which is sent to ballistic separation. Another stream of fines is separated and joined to the fines from the primary separation. Finally, the trommel overflow of the primary separation (or "oversize" stream) is made up of paper and cardboard with small amounts of plastic foils and containers.

At this point there are four material streams which will be processed on individual lines:

- The oversize stream has to be cleaned in order to produce the main product which is old newspapers and magazines. This is achieved by NIR (near-infrared spectroscopy) detection and removal of cardboard and plastics, followed by manual product quality control. The NIR sorter output is further split by a second NIR sorter into cardboard and plastic. The cardboard fraction joins, then, the 2D stream, while the plastic fraction is processed on a second ballistic separator in order to recover any plastic containers (thereafter sent to the main 3D line). The 2D material from this ballistic separation becomes a sorting residue.

- The main 2D, 3D and fines streams undergo magnetic and eddy current separation to remove ferrous and non-ferrous components. The 2D line, which has mixed paper as the main product, passes under a NIR which removes any contamination before a final manual quality control. The material separated by the NIR sorter is also sent to the second ballistic separator to recover any containers.
- The 3D line, after magnetic and eddy current separation, passes a NIR sorter which removes cardboard and paper (returned to the 2D line for further recovery). The remaining materials, largely now a concentrated stream of plastic containers, undergo a final quality check and pass through a bottle flattener before entering the polymer sorting block. In a sequence, clear PET, coloured PET, natural HDPE and coloured HDPE outputs are produced by NIR sorting. The leftover stream passes a final NIR sorter which removes any missed valuable polymers, then recirculated to the beginning of the 3D line.
- The fines line has the main objective of producing a clean glass cullet product (>12mm). This is achieved with a sequence of separation and cleaning processes, including screening, air density separation and final NIR sorting for removal of contaminants.

Differently than single-stream plants, sorting plants for dual-stream commingled dry recyclables have a separate line for fibre and container streams recovery. Much of the equipment in a dual-stream plant has a smaller throughput and capacity than a single-stream one for the same quantity of input-waste managed.

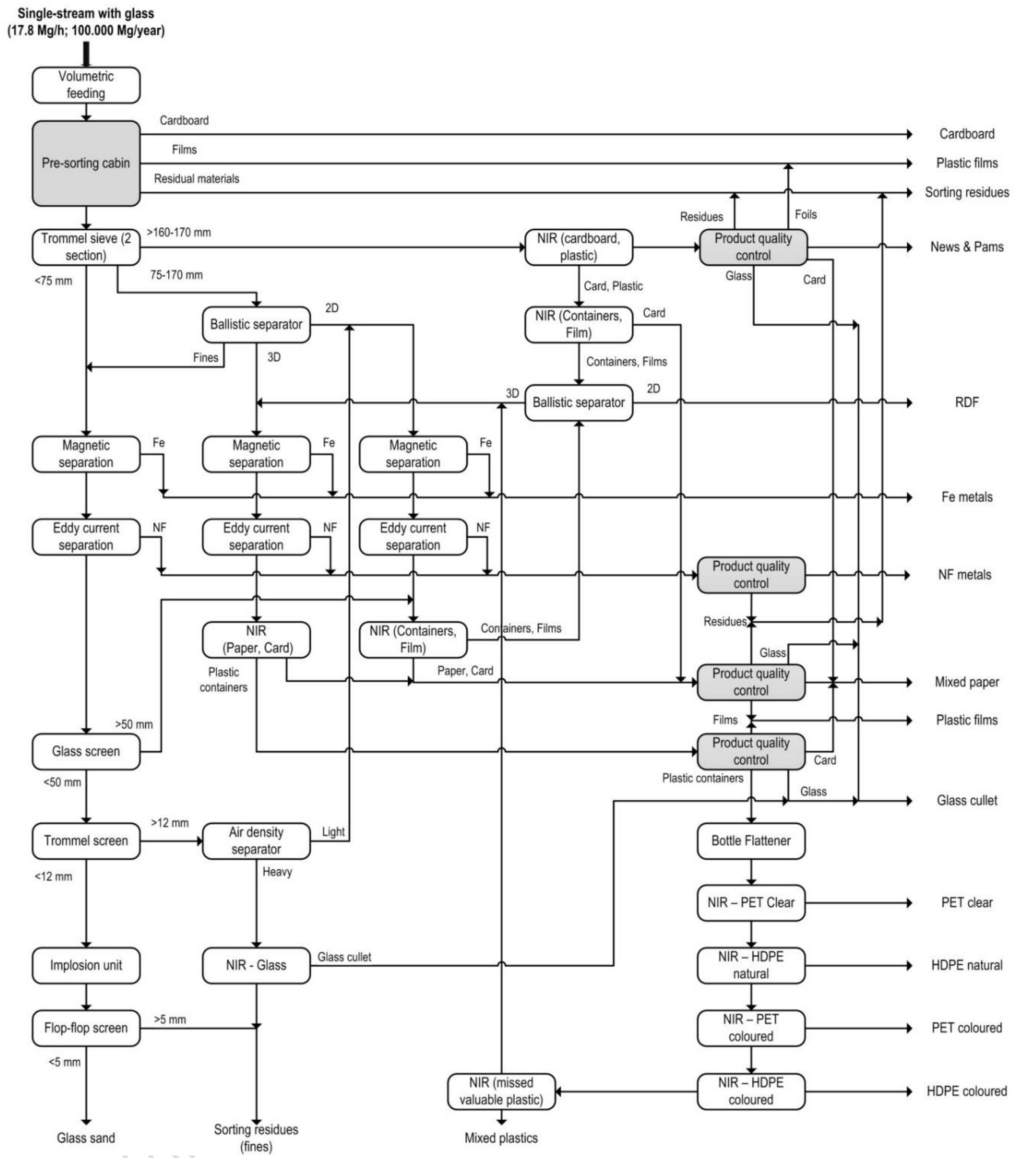


Figure 2. Example of sorting plant (material recovery facility) managing a single-stream commingled input of glass, metal, paper and cardboard, and plastic. Arrows represent conveyor belts. OCC: old corrugated cardboard; HDPE: high-density polyethylene; PET: polyethylene terephthalate. Taken from (Cimpan et al., 2015).

3.2.1.2 Sorting plant for lightweight packaging

An example of German plant for lightweight packaging sorting is illustrated in Figure 3 (figure and relative description taken from Cimpan et al., 2015). Bag opening is performed as a coarse shredding process in order to open bags and liberate materials. The materials then undergo a series of conditioning steps. The first conditioning step is sieve classification, performed with drum screens (trommels) with one or two functional separation cuts. This step has the functions of: (1) splitting the flow of materials in relation to the workable size spectrum of sorting equipment downstream; and (2) pre-enrichment of different materials. The proven cut-off for coarse materials is 220 mm. The screen overflow is typically 10-15% of the input stream, and is typically led to the separation of plastic films in an air classifier (light fraction). The heavy fraction from the air classifier can be manually sorted or shredded and returned to the medium-grain sorting lines.

The materials smaller than 220 mm, i.e. going through the drum screen, are separated in two to four further particle size intervals, with the last cut-off used for fine grain material, typically <20mm (the 'fines'; sent to disposal). The main mass flow, 20-220 mm, represents about 80-85% of the input stream and is now processed on two or three individual lines. First, air classification is used to remove further plastic films (typically 10% of the input stream). The next step is the separation of ferromagnetic components by magnets (9-13% of input stream). NIR sensor sorting is then used to remove beverage cartons (also called liquid carton containers; LCC). Eddy current separation is used to sort non-ferrous components (<5% of input). The reason beverage cartons are removed first is because they interfere and would be partially separated with non-ferrous material by the Eddy current.

In two more NIR sorting steps, paper/card packaging and all plastics are removed in mixed streams. The mixed plastics stream can be further conditioned, typically by using ballistic separators to remove fines and any remaining 2D material, before it enters the polymer sorting block. Here plastics are sorted in a cascade by polymer type in the four standard packaging polymers, i.e. HDPE, PP, PET and PS. Individual sorted polymers can undergo a second automatic "cleaning" step, or be refined by automatic colour sorting (typically only PET). The leftover plastics, after polymer sorting, will constitute typically a mix polymer product, however, another sensor unit can be used to pick remaining/missed value polymers (a "scavenger") and recirculate them to the start of the polymer sorting process, thus increasing recovery rates.

State-of-the-art plants can have up to a total 20 NIR sorting machines. In addition to NIR, multi-sensor systems are commonly used for specific tasks (combining NIR, colour or induction sensors). Some of these plants use additional sensing equipment for material and process surveillance. For this purpose, ultrasonic or VIS-camera based volume flow measurement devices are in use, which helps the plant operator to react on changes of the volumetric flow in the plant set up. In spite of the high level of automation, most of these systems need to be supported with additional manual quality control.

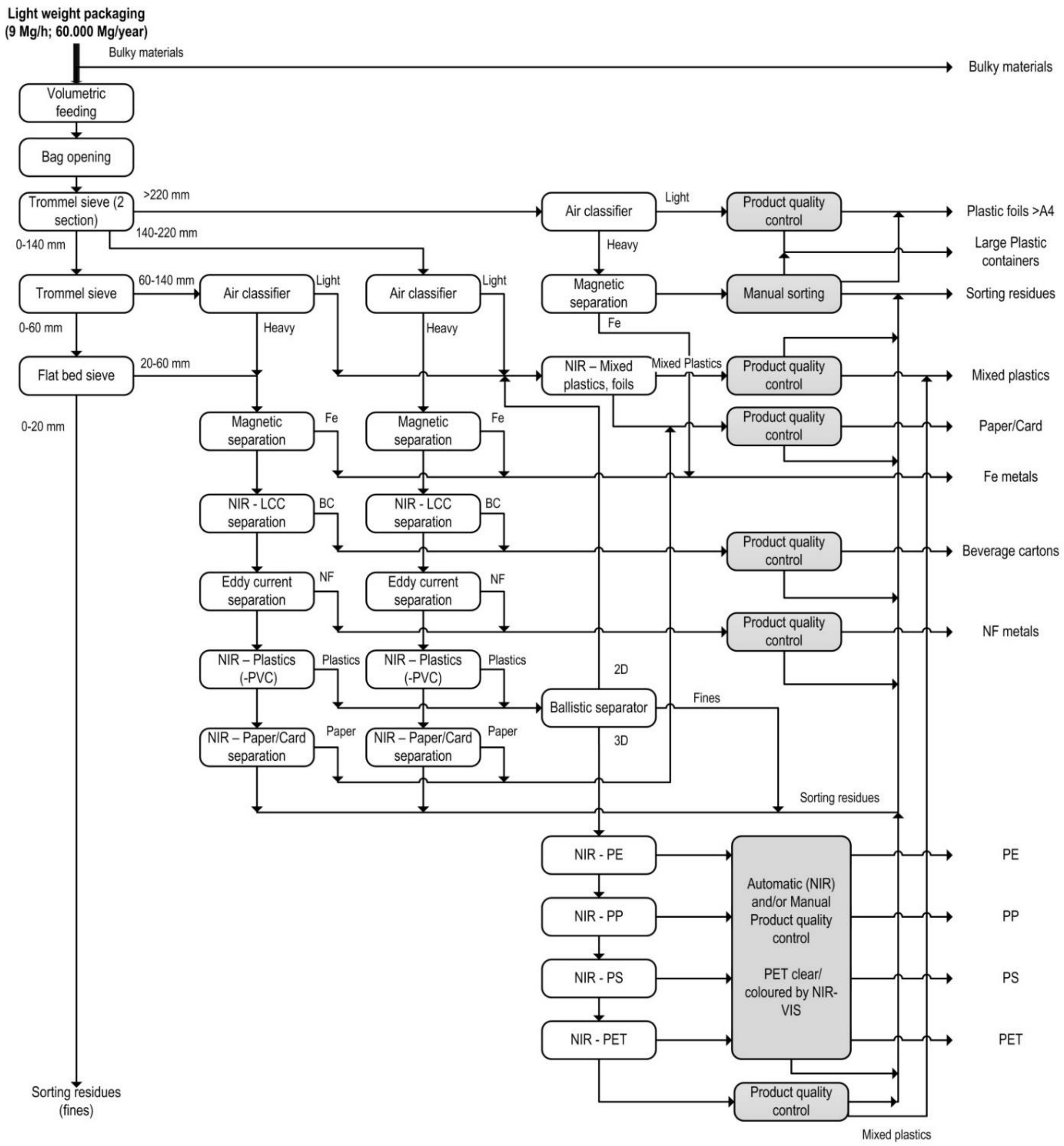


Figure 3. Example of sorting plant for lightweight packaging, i.e. managing an input of light packaging composed of plastic, metal, and beverage cartons (including other composite). BC: beverage cartons; OCC: old corrugated cardboard; HDPE: high-density polyethylene; LCC: liquid carton containers; NIR: near-infrared; PE: polyethylene; PET: polyethylene terephthalate; PP: polypropylene; PS: polystyrene; PVC: polyvinyl chloride; Taken from (Cimpan et al., 2015).

Box 1. Common problems of sorting plants in relation to the degree of commingling of the input-waste to be treated. Insights from operators in the field of collection and sorting.

Interview with HUB

1. Commingling of glass with plastic waste

Commingling glass with plastic waste is not ideal for the following reasons (implications at sorting):

- Glass waste commingled with other fractions often incurs formation of glass powder/fines, often ending up contaminating the plastic material.

- In the long-term glass waste brings problems of 'abrasion' to the equipment/machineries at sorting plant because of the formation of glass fines/powder.

- The presence of glass powder/fines in plastic waste creates a problem of quality management (quality control and monitoring of quality), because the fines are counted as impurities (notwithstanding being 'glass' which is a material commingled with plastic under this scenario)

2. Commingling of beverage cartons

Beverage cartons can be commingled with paper and cardboard, or in multi-material stream together with plastics and metals.

- Commingling beverage cartons with paper and cardboard typically incurs important losses at the mill (pulper) because the mills are generally not equipped with specific sensor for separation, as they are not waste treatment plants. Also, the aluminium and polymeric fractions could be not subject to recovery, for the same reason. Ultimately, losses and reduced efficiency may arise under this commingling scenario.

- Commingling beverage cartons with plastic and metal waste implies that at the sorting plant a sensor is installed (typically, 250-300k €). This has high amortisation cost due to the low nominal throughput (e.g. only 90,000 t of beverage cartons are placed on the market annually in Italy; a similar situation applies to remaining EU Member States).

3. Commingling of metal waste

- Metal waste needs to be commingled with other materials because separate collection is economically not feasible.

- The separation of metal waste via magnets and Eddy Current System (ECS) makes separation feasible and efficient both from mix of plastic, beverage cartons and metals and mix of metal and glass waste.

Interview with an Italian frontrunner operator

1. Commingling of glass with plastic waste

- Presence of glass hinders the quality of other fractions because of formation of fines. At the sorting plants glass fines causes problems of dispersion and affect the maintenance of the equipment in the long-term.

- On this basis, experience from the operator experts is that it is better to keep glass material separate (i.e. better a mono-stream collection dedicated only to glass).

- However, the operator also suggests that mixing glass with metals (commingling) is not a problem as metal separation from glass is relatively easy.

- Collection of glass should anyway be done with non-compacting systems to prevent excessive formation of fines because of glass breaks.

2. Commingling beverage cartons (e.g. Tetrapak®) and Aluminium foil:

- The operator, where it operates in the north-east of Italy, generally commingles aluminium foil with plastic materials because separation is easy at the sorting plant (Eddy Current Separation).

- The operator commingles tetrapack (beverage cartons) with paper because tetrapack content is relatively low (a few percent) and separation is easy.

- The operator experts also suggest that commingling tetrapack (beverage cartons) with plastic materials would also be a good option because tetrapack content is relatively low (a few percent) and separation via (additional) sensor at existing plastic-sorting (or multi-material sorting) plants is easy (by adding a sensor) and economically feasible because of the economy-of-scale (the alternative to have a sensor at the paper selection plant is typically more costly).

3. Sorting plant losses

Evidence from experience and analyses done by the operator suggest that indeed there seems to be a correlation between the quality of the collected waste (i.e. the level of its impurities) entering a material sorting plant and the material losses at the sorting plant itself; for example, the operator observed that given a collected waste-input with an impurity content of about 14% the losses at the sorting–plant were about 17%. This somehow suggests a correspondence between quality of collected material and subsequent 'performance' of the selection/sorting plant. The figures mentioned are for commingling of plastic, metal, glass. Glass and metal come out very 'clean' from the sorting process, while plastic still has some impurities (plasmix) that are further removed downstream (by further sorting) and then sent to incineration and landfilling. For plastic, the estimates are that 61% of the collected is then recycled and 36% is sent to incineration.

3.2.1.3 Advanced sorting systems: (additional) recyclables recovery from mixed waste

As described in section 2.3, the ‘paradigm’ of separate waste collection established by the Waste Framework Directive prioritises the separation of recyclable fractions based on its overall environmental benefit, but Member States may envisage derogations where duly justified, as in the case of some commingling.

Some advanced approaches may even go beyond the commingling of dry recyclables between themselves, and envisage the collection of some recyclables with residual waste. One approach in particular has been pioneered and tested in Norway[7], whereby some plastics are collected along with (and subsequently sorted from) mixed waste. This kind of approach rests on the following prerequisites, characteristic of an advanced and well-functioning separation system:

- bio-waste is collected separately, which lowers the level of contamination of residual waste with pathogens and other contaminants of the recyclable fraction to be recovered.

- Most dry recyclables are collected separately, either through bring/door-to-door systems (e.g. paper & cardboard) or through DRS (e.g. metal and glass drinks containers).

- Mixed waste separation is performed with extensive intervention of automated sorting equipment with high sorting efficiency (helping in particular to contain the labour costs of sorting, especially in high-wage economies).

If these preconditions are met, plastics recovered from residual waste may have comparable levels of contamination with plastics collected separately, enabling further processing and recycling to secondary materials with similar quality levels. These has been tested in dedicated sorting and recycling facilities in Norway and the quality of the secondary plastic material obtained resulted indeed comparable to that of separately collected plastic waste. Along with to plastic, other material is additionally recovered from the mixed residual waste such as ferrous and non-ferrous metals.

It should be noticed that this system, characterized by an advanced sorting of the mixed residual waste, is not alternative to separate collection but rather complementary. Indeed, most of the waste is still separately collected at the source, notably bio-waste, paper and cardboard and metal/glass drinks containers, which make up altogether about 60% of the generated MSW. The main difference therefore regards the management of the plastic waste (ca. 10% of the generated MSW), which is recovered from the mixed residual waste instead of being separately collected and commingled with other waste fractions (e.g. with metals and beverage cartons). The complementarity also lies in the fact that this sorting system allows to recover additional material (e.g. metals) from the mixed waste.

3.2.2 Recycling of dry recyclables

3.2.2.1 Recycling of glass waste

Glass manufacturing plants can use glass cullets together with conventional raw materials (limestone, $CaCO_3$, sand, SiO_2, and soda ash, Na_2CO_3) to lower the melting temperature and, therefore, reduce the energy needed for the production process. The glass waste goes through a pre-treatment process (sorting) which removes unwanted material (e.g. paper or plastic) normally using blown air. Further, metal objects are removed with magnets or eddy current system separators. Next, the waste flow is sorted by colour through optical sorting and washed to remove any further impurities. The pre-treated feedstock is then crushed and fed in the furnace (together with the primary material) to be melted, substituting conventional raw materials that would otherwise be used (limestone $CaCO_3$, sand, SiO_2, and soda ash, Na_2CO_3). Then, it is finally moulded into new products such as bottles and jars. Glass does not degrade through the recycling process so it can be recycled indefinite times.

[7] a Member of the European Economic Area (the WFD is a text with EEA relevance).

3.2.2.2 Recycling of metal waste

The reprocessing of steel is typically occurring via electric arc furnace (EAF) or basic oxygen furnace (BOF) (Damgaard et al., 2009). Prior to EAF or BOF, pre-treatment (sorting) operations take place to remove unwanted items. The BOF process accepts only 25–30% of scrap steel, while the EAF process accepts 100% steel scrap and this is where the majority of the post-consumer steel scrap ends up. The main steps of the EAF process are as follows. The scrap is first preheated with the off gas generated at latter steps in order to conserve energy (and optionally additional fossil energy can be added). Next, the scrap is loaded in baskets together with lime, which is used as a flux. The furnace anodes are then lowered into the scrap. The initial energy to the arcs is kept low, until they are fully submerged in the scrap at which point the energy is increased until complete melting. Oxygen can be added to the early stages of the melting to boost the process. When the final temperature has been reached, the liquefied steel is tapped into a ladle, and alloying and deoxidizing compounds are added. After this, the steel is sent for casting to produce any kind of final product.

Aluminium recycling mainly takes place in rotary or reverbatory furnaces; for very clean aluminium grades, induction furnaces can be used but these take up a very small part of the aluminium recycling (Damgaard et al., 2009). For the aluminium collected via MSW, (e.g. beverage cans and foils), it is necessary to pre-treat the aluminium to remove contaminants and de-coat or de-oil the scrap. This improves the thermal efficiency of recycling and reduces potential emissions from the melting process. After pre-treatment, the scrap is loaded into the furnaces. There are a number of different furnace setups depending on the quality of the aluminium scrap. From the furnace the melted aluminium is tapped for either direct casting or sent to another furnace where alloys can be made. In this process the aluminium is also refined to remove the remaining impurities in the product. Typically, the aluminium recycling process only uses around 5% of the energy needed for the virgin aluminium production, as the alumina conversion in virgin production is responsible for the majority of the energy consumption (Damgaard et al., 2009).

3.2.2.3 Recycling of paper and cardboard waste

There are two main groups of reprocessing of paper and cardboard into pulp: mechanical and chemical-mechanical re-pulping (Merrild et al., 2009). Mechanical re-pulping consists of re-pulping, mechanical removal of large contaminants, refining by washing, sorting, and milling, mechanical removal of finer contaminants, thickening and optional bleaching, and final drying. Mechanical pulping is used for production of paper of lower grades. Chemical re-pulping, in addition to the steps listed above, includes also de-inking to brighten up the pulp for use in higher value paper grades such as printing and copy paper for which such parameter is important. The process of de-inking involves a chemical step where agents are added to free the ink from the pulp and a mechanical step of flotation where the removed ink is finally physically separated from the rest of the pulp. De-inking normally occurs after the refining step.

3.2.2.4 Recycling of plastic waste

Plastic waste can either be recycled through mechanical/physical (also referred to as ‘material recycling’ in literature) or chemical recycling. With the former, the molecular structure of plastic is preserved, while with the latter the polymer chains are converted into its oligomers, monomers or other basic chemicals such as carbon monoxide, carbon dioxide, methane, and hydrogen (Delva et al., 2019). In a recent publication, Collias et al. (2021) distinguishes material recycling into mechanical and physical recycling (i.e. dissolution or solvent-based recycling), and chemical recycling into depolymerisation, gasification and pyrolysis. These recycling processes can be further classified into polymer loops, monomer loops, and molecular loops. Material recycling belongs to the polymer loop as the output obtained from this reprocessing is the purified form of the same input plastic waste that was originally fed into the process (Collias et al., 2021). Depolymerisation is classified as a monomer loop as the input plastic waste is converted into its constitutive monomers, while pyrolysis and gasification are classified as molecular loops as the input plastic waste is converted into smaller molecules or group of molecules (e.g. carbon monoxide, carbon dioxide, hydrogen, methane) prior to further reprocessing into monomers/polymers (Collias et al., 2021). A detailed description of chemical recycling processes may be found elsewhere (notably, (Caro et al., 2022; Jeswani et al., 2021; Kusenberg et al., 2022; Manžuch et al., 2021; Ragaert et al., 2017; Solis & Silveira, 2020)).

Mechanical recycling is only suitable for thermoplastic materials as thermoset plastic cannot be re-melted. This recycling technology involves physical processes that can occur either at all or multiple times, and are as follows: cutting/shredding into small flakes; contaminant separation (removal of impurities such as paper and dust via a cyclone); floating (separation into different types of plastic according to their density); milling (for separate, single-polymer plastic); washing and drying; agglutination (after the addition of pigments or additives, the product can either be stored and sold at a later stage or sent to further processing); extrusion (extrusion to strand); pelletizing; and, quenching (water cooling to granulate the plastic and sell it as a final product) (Al-Salem et al., 2009). The focus of this document and modelling is on mechanical recycling, being chemical recycling currently dealing with a negligible fraction of the plastic waste.

3.2.2.5 Recycling of beverage carton waste

Beverage cartons are a composite material composed of fibre board (ca. 72.5%), polymer (ca. 24%) and aluminium (ca. 3.5%) (Zero Waste Europe, 2020). Due to its composite nature, beverage cartons cannot be easily recycled by paper mills that recycle regular paper-based packaging, as the latter has a too short delamination process that would not allow a correct separation of all layers composing beverage cartons. Therefore, beverage cartons need to be processed in dedicated paper mills. As of today, 20 such paper mills exist across Europe; the first step is to separate the fibres from the other layers of the packaging in a paper mill utilising different special dissolving technologies. The fibres can be used to produce new paper products, while the remaining aluminium and polymers are recovered and can be recycled at dedicated plants[8].

[8] https://www.beveragecarton.eu/wp-content/uploads/2021/10/ACE-Recycling_BROCHURE_September-2021.pdf.

4 Environmental and socioeconomic impact according to separation and collection practices

4.1 Life cycle assessment (LCA) methodology

This section details the life cycle assessment (LCA) methodology used in the study to quantify the environmental impacts of the management in the EU27. The LCA has been carried out in accordance with the guidelines of the ISO 14040/14044 standards (ISO, 2006a, 2006b). It should be notice that the methodology and the inventory data used in this study largely builds on the waste management assessment model developed by the authors and detailed in a parallel publication (Albizzati et al., 2023). While we will strive to report and describe the methodological choices and inventory data that are key to this specific study, additional information and data on the modelling of waste management may be consulted in (Albizzati et al., 2023).

To address the performance of collection schemes in the modelling, we focus the modelling on the following key main parameters of the waste management system:

- The capture rate of each individual material; based on scientific-technical evidence available.
- The impurity content of each individual material collected; based on scientific-technical evidence available.
- The sorting (and recycling rate) and consequent losses; based on the level of impurities entering the sorting from (2), i.e. via mass–balance (aka material flow analysis modelling).
- The expected sorting rate per material, considering the level of commingling of the input to the sorting plant; based on scientific-technical evidence available.

4.1.1 Goal, scope, and functional unit of the study

The scope of the LCA is the separate collection of dry recyclables (beverage cartons, glass, metals, plastic, paper and cardboard) and their subsequent management operations until final recovery or disposal of the waste. The subsequent management operations include therefore sorting, recycling, incineration, landfilling and transport operations. The overarching goal is quantifying environmental impacts, costs and employment effects associated with the alternative management schemes that can be employed throughout the EU27 to collect and subsequently manage dry recyclables.

The functional unit of the LCA, which defines qualitatively and quantitatively the service under assessment, is "the management of 1 tonne (wet) of dry recyclables in the EU27, with the material fraction composition and physico-chemical properties based on (Edjabou et al., 2021) and (Götze et al., 2016), respectively". Specifically, based on the Eurostat statistics and on the information reported in the EEA's Early Warning assessments, it is estimated that out of the 1 tonne (wet) of dry recyclables 42% is paper and cardboard, 24% is plastic waste, 20% is glass waste, 11% is metal waste, and 3% is beverage cartons waste. Note that waste management encompasses different processes, and a number of products arise from the valorisation of the waste, notably recyclates, heat, electricity. How to handle such processes and outputs is described in section 4.1.3.

The environmental impacts were quantified following the Environmental Footprint Life Cycle Impact Assessment method (EF, v3.0) (EC-JRC, 2012). The following 16 impact categories included in the EF v3.0 method were considered: Climate Change; Ozone Depletion; Human Toxicity, cancer; Human Toxicity, non-cancer; Particulate Matter; Ionising Radiation; Photochemical Ozone Formation; Acidification; Eutrophication, terrestrial; Eutrophication, freshwater; Eutrophication, marine; Ecotoxicity, freshwater; Land Use; Water Use; Resource Use, minerals and metals; Resource Use, energy carrier. The LCA software EASETECH v3.4.0, specifically developed to assess waste and technology systems (Astrup et al., 2012; Clavreul et al., 2014), has been used to model the waste management scenarios.

4.1.2 Scenarios assessed

As described earlier (section 3), dry recyclables can be collected separately as individual mono-streams or commingled in different ways. To cover the possible combinations, we assess a number of fifty-five scenarios that are illustrated in Table 1. Notice that in Table 1 beverage cartons are either commingled (displayed) or directly disposed of with the residual waste (not displayed) as this seems to be a practice still in many regions across the EU. Notice that the residual waste bin and bio-waste bin are not included in the number of bins, and, thus, not displayed in Table 1; yet, they are part of the overall MSW collection system. So, if the reader wants to know the total number of bins a household will have, he/she should simply add '+2' to the bins displayed for dry recyclables, as we assume these two to be separately collected as mono-stream in line with the obligations of the WFD.

The scenarios assessed cover the most common commingling systems in EU27 that we identified (as described in 3.1) and are expanded to include other commingling systems that appear to be relevant in the analysis. The scenarios included in our analysis cover:

- All separate streams for each dry recyclable;
- Commingling of plastic, metal, beverage cartons;
- Commingling of paper and cardboard, plastic, metal, beverage cartons;
- Commingling of metal, plastic;
- Commingling of paper and cardboard, glass, metal, plastic;
- Commingling of paper and cardboard, beverage cartons;
- Commingling of glass, metal;
- Commingling of plastic, beverage cartons;
- Combination of different commingling systems;
- DRS on glass bottles, plastic bottles, and metal cans.

Among the possible commingling setups, the collection of glass together with metal and plastic has been excluded. Despite this practice being employed in some Italian locations, it was decided to exclude it as evidence has already shown that this practice is not beneficial neither for plastic, glass, nor for the machinery. Indeed, (Neidel & Kromann, 2019)[9] found that this commingling setup hinders the quality of the glass making it not compliant with standards for packaging glass production as current technologies are not able to remove small plastic items. Further, glass is also detrimental for the selection machinery itself as it wears it and affects its maintenance in the long term. Finally both evidence from operators (see Box 1 at section 3.2.1) and from (Neidel & Kromann, 2019) (see in particular the English summary) indicates that the glass fines/powder hinder the quality of plastic sold to recyclers. In Italy, this practice is actually being banned due to the evidence collected against it. In our assessment glass is assumed only to be commingled with metal or with paper and cardboard, plastic, and metal as these are practices that were observed being widespread within EU27.

[9] Report from the Danish Ministry for Environment and Food. Available at: https://mst.dk/service/publikationer/publikationsarkiv/2019/feb/analyse-af-miljoe-og-oekonomi-ved-kildesortering-og-kildeopdeling/ (access January 2023).

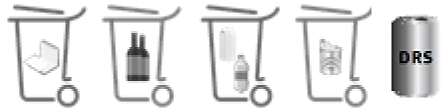
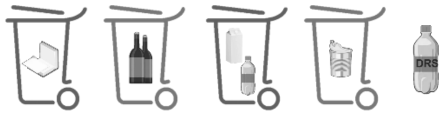
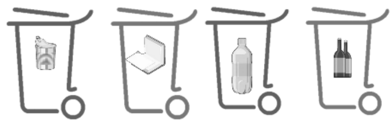
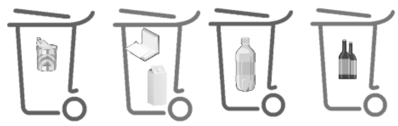
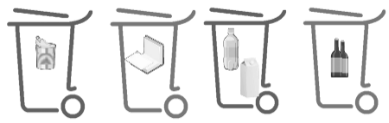
Table 1. List and description of scenarios considered in the analysis. The counting on the number of bins excludes one bin for residual waste and one bin for bio-waste. Therefore, the total number of bins is the one indicated under "Number of bins" +2. The following acronyms are used: "BC" waste beverage cartons; "DRS" deposit refund system; "GL" glass waste; "PC" paper and cardboard waste; "PL" plastic waste; MT metal waste. Commingling is indicated between brackets, e.g. (MT+PL) means metal and plastic collected together. For a detailed breakdown of the composition of beverage cartons, glass, paper and cardboard, and plastic in terms of material fractions refer to Annex A.

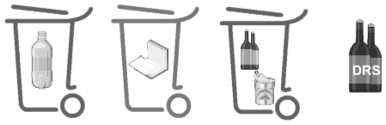
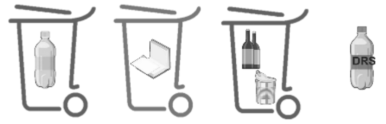
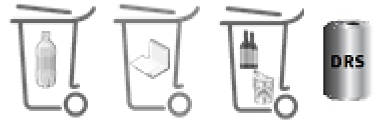
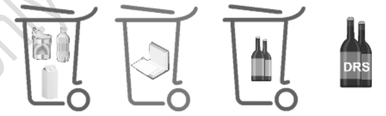
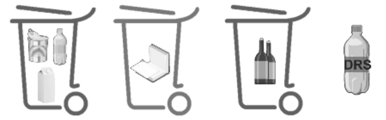
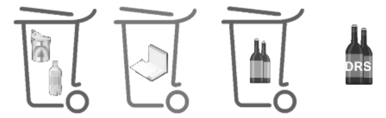
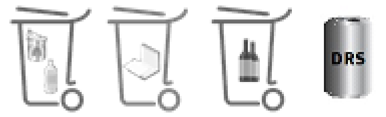
Legend

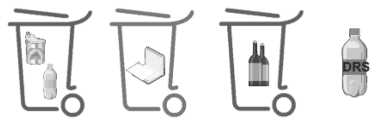
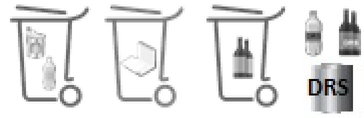
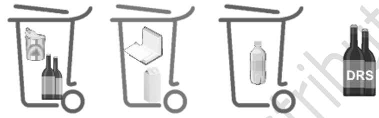
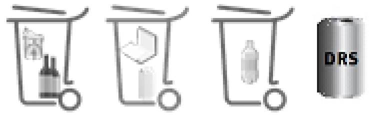
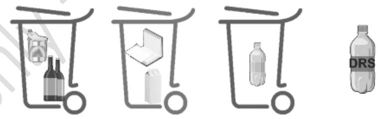
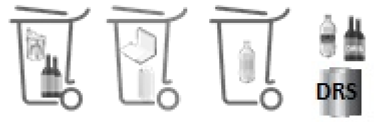
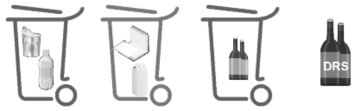
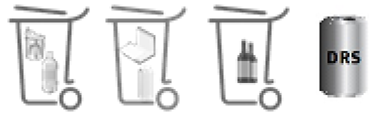
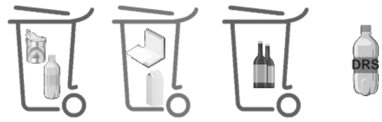
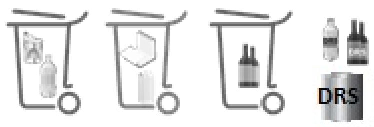
Paper and cardboard waste	Glass waste	Metal waste	Plastic waste	Beverage cartons waste
				

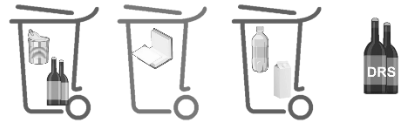
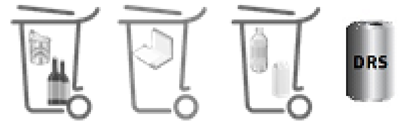
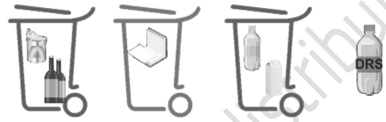
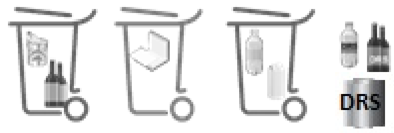
DRS on glass bottles	DRS on plastic bottles	DRS on metal cans
		

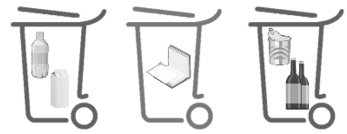
System (No of streams)	Acronym of scenario	Description
4-stream&DRS	DRS GL & all separate streams	
	DRS MT & all separate streams	
	DRS PL & all separate streams	
	DRS & all separate streams	
	DRS GL & (PC +BC)	

	DRS MT & (PC + BC)	
	DRS PL & (PC + BC)	
	DRS PL, MT, GL & (PC + BC)	
	DRS GL & (PL + BC)	
	DRS MT & (PL + BC)	
	DRS PL & (PL + BC)	
	DRS PL, MT, GL & (PL + BC)	
4-stream	All separate streams	
	(PC + BC)	
	(PL + BC)	

3-stream&DRS	DRS GL & (GL + MT)	
	DRS MT & (GL + MT)	
	DRS PL & (GL + MT)	
	DRS PL, MT, GL & (GL + MT)	
	DRS GL & (MT + PL + BC)	
	DRS MT & (MT + PL + BC)	
	DRS PL & (MT + PL + BC)	
	DRS PL, MT, GL & (MT + PL + BC)	
	DRS GL & (MT + PL)	
	DRS MT & (MT + PL)	

	DRS PL & (MT + PL)	
	DRS PL, MT, GL & (MT + PL)	
	DRS GL & (PC + BC) & (GL + MT)	
	DRS MT & (PC + BC) & (GL + MT)	
	DRS PL & (PC + BC) & (GL + MT)	
	DRS PL, MT, GL & (PC + BC) & (GL + MT)	
	DRS GL & (PC + BC) & (MT + PL)	
	DRS MT & (PC + BC) & (MT + PL)	
	DRS PL & (PC + BC) & (MT + PL)	
	DRS PL, MT, GL & (PC + BC) & (MT + PL)	

	DRS GL & (GL + MT) & (PL + BC)	
	DRS MT & (GL + MT) & (PL + BC)	
	DRS PL & (GL + MT) & (PL + BC)	
	DRS PL, MT, GL & (GL + MT) & (PL + BC)	
3-stream	(GL + MT)	
	(MT + PL + BC)	
	(MT + PL)	
	(PC + BC) & (GL + MT)	
	(PC + BC) & (MT + PL)	

	(GL + MT) & (PL + BC)	
2-stream&DRS	DRS GL & (PC + PL + MT + BC)	
	DRS MT & (PC + PL + MT + BC)	
	DRS PL & (PC + PL + MT + BC)	
	DRS PL, MT, GL & (PC + PL + MT + BC)	
2-stream	(PC + PL + MT + BC)	
1-stream&DRS	DRS GL & (PC + GL + MT + PL)	
	DRS MT & (PC + GL + MT + PL)	
	DRS PL & (PC + GL + MT + PL)	

	DRS PL, MT, GL & (PC + GL + MT + PL)	
1-stream	(PC + GL + MT + PL)	

4.1.3 System boundaries

The system boundary includes all the operations involved in the life cycle of the waste once this is generated, i.e. separation at home, collection (intended as the collection and hauling to the first treatment facility), sorting plant for dry recyclables, incineration, landfill or other treatments (centralised sorting or MBT) for the mixed residual waste, transport (i.e. transport of sorted bales to recycling plants; recyclates to the market; bottom ash to final disposal; etc.), recycling, and other operations that may be required prior to final recovery or disposal (e.g. bottom ash treatment).

The generated waste is assumed to carry no prior environmental burden (prior to becoming a waste) following the so-called "burden-free" assumption that is often applied in LCA of waste management (Laurent, Bakas, et al., 2014; Laurent, Clavreul, et al., 2014). The impact of production would anyway be the same across all scenarios, as all scenarios treat exactly the same input-waste (i.e. the functional unit, as described in section 4.1.1). Additionally, managing waste generates useful outputs such as recyclates and energy. This is called "multi-functionality" because the management system delivers multiple functions additionally to the main service strictly consisting in managing the waste. To address this multi-functionality, the so-called system expansion approach was applied following common practice in waste management LCA (ISO, 2006a, 2006b) (Laurent, Bakas, et al., 2014; Laurent, Clavreul, et al., 2014). Accordingly, the products generated along with managing the waste (e.g. recyclates, electricity and heat, compost, digestate, bottom ash) were credited to the waste management system by assuming the displacement of the corresponding market products obtained from virgin material (i.e. recyclates are assumed to substitute corresponding virgin material production) or from conventional energy sources (i.e. electricity and heat from waste incineration are assumed to substitute electricity and heat produced from conventional energy sources in the EU27) as illustrated in Figure 4. In other words, the substitution of materials and energy incurs environmental savings (credits) that are attributed to the waste management system in a similar fashion as for the economic revenues.

Notice that such system expansion is a common approach used in waste management LCAs and is also in line with the end-of-life approach of the EC EF-Method (European Commission Environmental Footprint Method). To represent the substituted materials (notably plastic, glass, metals, paper and cardboard), the current market average for those products was used (see previous JRC study; (Albizzati et al., 2023)) relying on background datasets taken from the ecoinvent 3.8 database (Wernet et al., 2016). To model the substitution of electricity and heat in the year 2020 we used the EU electricity and heat mix as detailed in the official GECO projections of the European Commission JRC (GECO reports; (Keramidas et al., 2018) and subsequent updates).

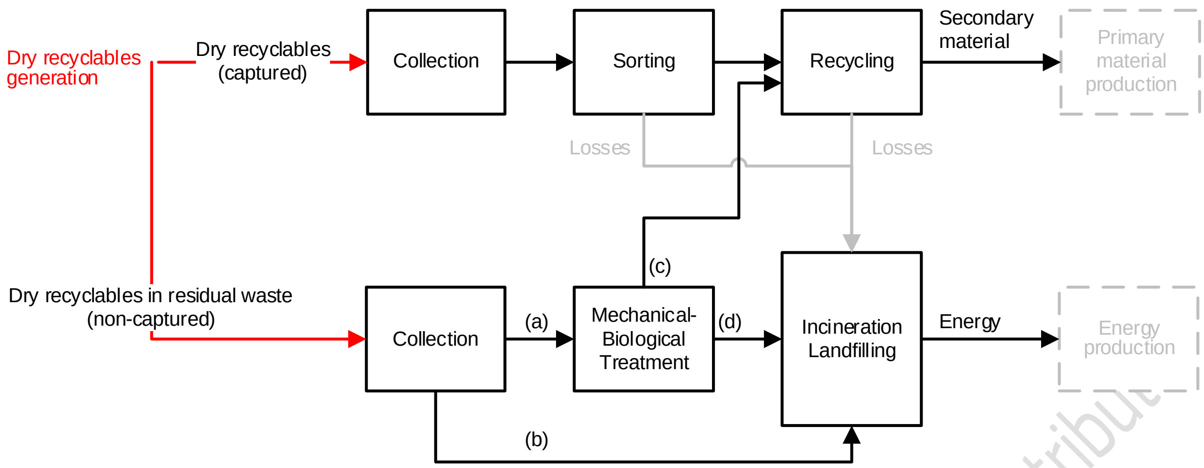


Figure 4. Generic system boundary for the LCA of dry recyclable waste management. Dry recyclables are collected either individually or commingled (various combinations are possible; here we keep it very general) and sent to sorting and recycling. The share of dry recyclables that is not captured is collected together with the residual waste and sent to centralised sorting or MBT (a) for further selection or directly to incineration or landfilling (b). The output of the mixed waste sorting can be sent to partly recycling (c) and partly incineration and landfilling (d), depending upon the sorting plant material recovery rates. Black-continuous boxes indicate induced processes, while grey-dashed boxes indicate avoided processes (substitution of energy and virgin material, i.e., credits for waste valorisation) following the so-called system expansion approach (ISO, 2006a, 2006b).

4.1.4 Life cycle inventory

Two levels must be differentiated: the foreground system, where waste treatment technologies and processes are modelled, and the background system, which determines the choice of inventory data.

The foreground system refers to all those processes of the waste management, like collection, sorting, recycling, incineration, landfilling, on which the policy maker can have a direct influence via this specific study or its implications thereof. Each stage of the waste management system was modelled in the dedicated waste-LCA model EASETECH 3.4.0 using input-data from the scientific and technical literature.

The background system refers to all those processes that are used in the waste management operations, such as electricity/heat or chemicals/material supply, but on which the policy maker has not direct influence via this specific study or its implications thereof. For all the background processes, datasets from the Ecoinvent 3.8 database (allocation at the point of substitution; (Wernet et al., 2016) were used.

For the collection of plastic, fuel consumption was based on (Andreasi Bassi et al., 2022) (average value 0.00335 L/kg), for paper it was based on (Larsen et al., 2009) (average value 0.00406 L/kg), for glass on Larsen et al. (2009) (Table 4), for metals and commingled dry recyclables on (Jaunich et al., 2016) (average value 0.02023 L/kg), for bio-waste on (Gredmaier, L., Heaven, S., Vaz, 2013) (average value 0.00808 L/kg), and for residual waste on Larsen et al. (2009) and Jaunich et al. (2016) (average value 0.0048 L/kg). With respect to collection rates and presence of impurities for the different collection systems, the data presented in Annex A was used in the study. Notice that both for the physical and cost data, the 75th percentile of the data was taken.

With respect to sorting of dry recyclables, glass recycling, plastic recycling, aluminium recycling, energy recovery, landfilling, and mechanical biological treatment, the same modelling as in Albizzati et al., 2023 was applied. Notice that recycling of paper is based on ecoinvent processes, while steel recycling is based on PEF processes.

4.1.5 Sensitivity analyses

We performed sensitivity analyses on two key framework assumptions that apply across all the scenarios:

- The capture rate of plastic waste, which is very poor on average from the data collected. This is done by changing the capture rate of plastic waste from that used by default in each scenario (which depends on the separation and collection scheme assumed in each scenario; see Annex A) to the improved rates suggested in Antonopoulos et al. (2021) for best practices (remaining assumptions unchanged).

- Inclusion of a centralised sorting of residual waste prior to its incineration and landfill to recover additional mass of dry recyclables from the residual waste. This is done by modelling a sorting plant average for EU based on the data collected by Montejo et al. (2013).

The aim of these sensitivity analyses is to show the benefits of plastic recycling and further centralised material recovery in terms of environmental impacts, especially climate change and resource depletion, and of recycling rate.

4.2 Life cycle costing (LCC) methodology

4.2.1 General life cycle costing considerations

Monetising and extending the environmental assessment, the overall life cycle economic impacts of managing MSW were calculated using a life cycle costing (LCC) approach, following state-of-the-art approaches for waste management economics as detailed in (Hunkeler et al., 2008; Martinez-Sanchez et al., 2015). The LCC shares the same object, scope, functional unit, and system boundaries as the life cycle assessment (LCA). The cost assessment included two types of costs: internal costs and externalities (external costs). Internal costs include budget costs and transfers; strictly, budget costs are costs incurred by the different actors involved in the management chain of municipal solid waste (collectors, operators, transporters, etc.), while transfers refer to money redistributed among stakeholders (taxes, subsidies, value added tax - VAT, and fees). In our analysis, for the purpose of simplicity, we will refer only to the aggregated internal costs.

Externalities are non-monetary transactions representing the costs caused by each emission to society, reflected by the so-called shadow prices of emissions as proposed in (Bijleveld et al., 2018). Notice that these include prices for air/soil/water emissions but not for disamenities such as nuisance, noise, odour, congestions, time spent or other similar social effects. Notice that any externality priced in (e.g. in form of a tax) by an authority and paid by a stakeholder within the management system becomes a transfer, i.e. an internal cost.

As for terminology, we distinguish two types of LCC: the conventional LCC (CLCC) describes the financial cost, as sum of budgets costs and transfers, of managing the waste reflecting a classic financial assessment. The societal LCC (SLCC) sums the internal costs to the external costs, both expressed as shadow prices[10], to quantify the total cost carried by the society, thus reflecting a socio-economic assessment.

No discounting or inflation was applied to costs or externalities occurring in the future. All costs that were found in the literature or collected as primary data were adjusted for inflation to EUR2020. Capital investments (CAPEX) were first amortised, assuming a 5% market interest rate, and then annualised using a 20-year lifetime for buildings and 7-year for equipment, as suggested in (Martinez-Sanchez et al., 2015). Maintenance and insurance were accounted for and assigned to the OPEX.

The CLCC also allows deriving the total employment induced by the waste management system, expressed as full-time equivalent jobs per tonne of waste managed (FTE/tonne). For the specific shadow price of CO_2 we used the updated figure suggested by CE Delft and DG MOVE for 2030, i.e. 100 €$_{2016}$/tonne CO_2 that is recommended as default value, with a min-max range 60-189 €$_{2016}$/tonne CO_2 (van Essen et al., 2019). The remaining internal costs (based on literature) and external prices (using the report from CE Delft; Bijleveld et al., 2018) were kept constant between 2020 and 2030, in the absence of specific information. The LCC was implemented using the software EASETECH v3.4.0 (Astrup et al., 2012; Clavreul et al., 2014).

[10] In the CLCC, budget costs are accounted for in "factor prices" (market prices excluding transfers). Internal costs costs are then the sum of budget costs expressed as factor prices (market prices) plus transfers. Instead, budget costs in the SLCC should be accounted for in "shadow prices" (also called accounting prices or opportunity costs, and representing the willingness to pay for a good or service). Thus, when reporting the internal costs costs in the SLCC one should in principle remove the transfers and recalculate the remaining budget costs as shadow costs (e.g. the literature suggests the following calculation: market price x 1.325; (Martinez-Sanchez et al., 2015). In this analysis, we assume that the shadow price (of the SLCC) is equal to the internal costs price (of the CLCC), which implies assuming perfect market conditions. This approach was also taken in recent life cycle costing studies e.g. Albizzati et al. (2021).

4.2.2 Key cost inventory and assumptions

The unit-cost (EUR2020/tonne) for waste management processes and treatments were collected from scientific and technical literature. For details on collection, please refer to Annex A, while unit-cost data for waste sorting, recycling, incineration, landfilling, transport and other waste treatments and processes were collected from various sources, notably the EU reference model for waste (Eionet, 2018) and recent publications on plastic waste (Andreasi Bassi et al., 2020, 2022). More details on the unit-costs used to model the waste management may be found in (Albizzati et al., 2023).

4.2.3 Estimation of employment

The number of total employment in each waste management scenario assessed is quantified by knowing the amount of labour (full-time equivalent jobs per tonne managed; FTE/tonne) required for each waste process or management operation. The sum of the labour across the individual stages constituting the life cycle of the waste provides the total employment required to manage the dry recyclables (i.e. the service under assessment). This includes all the employees required to manage the dry recyclable from generation to final recovery or disposal, but does not include any reduction in employment elsewhere due to the waste management operations (e.g. following increased plastic recycling, one may argue that some job displacement occurs in the primary production of virgin plastic).

4.3 Results of the environmental and socio-economic impact assessment

4.3.1 Environmental impacts

4.3.1.1 Climate Change

The results obtained for the category Climate Change are herein described. It should be noticed that throughout the description of the results we will use the term 'bin' as a synonym of '(waste) stream', in a rather old-fashioned way. We are aware that some innovative collection systems are developed where in one bin two (waste) streams are collected to optimize logistics and decrease collection costs. However, within this study, this special case still belongs to a '2-bin' (i.e. 2-stream) system, for the sake of simplicity in the narrative and graphics.

Positive net results reflect burdens on climate change, while negative (below zero) reflect savings. In other words, if the results are below zero it means that the sum of the GHG emissions associated with the management of the waste is more than compensated by the sum of the avoided GHG emissions thanks to valorisation of the waste via recycling and energy recovery.

Figure 5 shows the relationship between net Climate Change impacts and the total recycling rate for dry recyclables (ranging from 9% to 49%). A linear regression was performed on the data (shown by the trendline in Figure 5), while the goodness-of-fit is indicated by the R^2 value that, indeed, represents how well the regression predictions fit the actual data, considering that the higher the R^2 the higher the fit. The R^2 value obtained equals 0.89 thus indicating a fairly good fit of the linear regression with the data points.

The trend observed in the results suggests that:

- Systems with a degree of separation of 3 streams (3-bin) or 4 streams (4-bin) perform significantly better than systems with a lower degree of separation (or higher degree of commingling; i.e. 1- or 2-bin systems).
- There is no clear evidence that 4-bin systems perform better than 3-bin systems. This tells that a certain degree of commingling is acceptable and does not seem to lead to detrimental environmental effects compared to systems with a lower degree of commingling (or higher degree of separation).
- Generally, the higher the recycling rate, the lower the net Climate Change impact of the waste management system.

The clusters performing the worst are the 1-bin&DRS (DRS on glass bottles *and* DRS on metal cans *and* DRS on plastic bottles, and the joint effect of the three, coexisting with single-stream commingling of paper and cardboard, glass, metal, and plastic) and 1-bin (single stream commingling of paper and cardboard, glass, metal, and plastic), where the net Climate Change impacts is about 328-330 kg CO_2-eq tonne^{-1} of dry recyclables and the corresponding total recycling rate equals 9%, thus indicating poor recovery of recyclables.

By increasing the number of bins, it is clear from Figure 5 that the net Climate Change impacts decrease and the total recycling rate increases, due to the higher recovery of recyclables. Specifically, the clustering of scenarios performing the best appears as 3-stream&DRS. More specifically, the scenario with DRS on glass bottles, metal cans, and plastic bottles coexisting with commingling of glass and metal, and commingling of plastic and beverage cartons performed best (net Climate Change impact of -234 kg CO_2-eq tonne^{-1} of dry recyclables and total recycling rate of 49%).

The burdens on Climate Change are mainly driven by incineration (contributing by 27-53% depending on the cluster; see Annex A), and recycling operations (contributing by 4-17% depending on the cluster, see Annex A). The savings are mainly driven by material recovery (contributing by 12-40% depending on the cluster; see Annex A) and energy recovered from incineration of residual waste (contributing by 11-20% depending on the cluster; see Annex A).

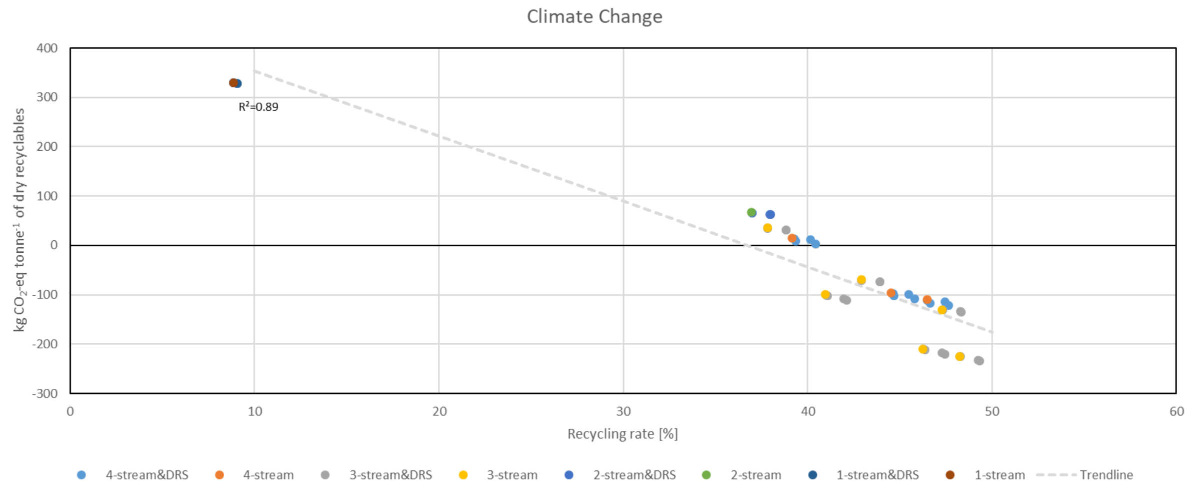


Figure 5: Net impacts on Climate Change (y-axis, expressed as kg CO_2-eq tonne^{-1} of dry recyclables) versus total recycling rate of dry recyclables (x-axis, expressed as %). The linear trendline calculated based on the results is shown together with the related R^2 value.

In Figure 6 the net results obtained for Climate Change are plotted via a box and whisker plot against the degree of separation, i.e. the clustering of the scenarios based on the number of streams for recyclables (e.g. mono-stream, dual-stream, etc.). We do this plot for two reasons: i) to offer another angle on the distribution of the results obtained and ii) to identify which degree of commingling achieves lower performances and is thus not recommended. The span of each box represents the interquartile range, which represents where 50% of the results lay. The interquartile range is calculated as the difference between the third quartile (upper end of the box, which represents the value under which 75% of the results are found) and the first quartile (lower end of the box, which represents the value under which 25% of the results are found). The box plot is shown together with the upper (where the end indicates the maximum result) and lower (where the end indicates the minimum result) whiskers, the median net result (horizontal line within the each box), and the average net result (cross within each box) (Figure 6).

As it was described in section 4.1.2, the scenarios clustered in 4-stream&DRS, 4-stream, 3-stream&DRS, and 3-stream cover the majority (80%) of the different combinations of collection schemes considered herein. The maximum Climate Change results obtained for these clusters are therefore used as benchmark (reference line) to identify which collection schemes should be avoided as leading to poorer performance (both for the category Climate Change and for recycling rate; red shaded area in Figure 6). Based on this logic, 2-stream&DRS, 2-stream, 1-stream&DRS, and 1-stream systems performs appear clearly worse than the remaining systems. These worst-performers correspond to the following specific scenarios:

- DRS on plastic bottles coexisting with commingling of paper and cardboard and beverage cartons, and commingling of glass and metal;
- DRS on glass bottles *and* DRS on metal cans *and* DRS on plastic bottles, and the joint effect of the three, coexisting with commingling of paper and cardboard and beverage cartons, and commingling of metal and plastic;
- DRS on glass bottles *and* DRS on metal cans *and* DRS on plastic bottles, and the joint effect of the three, coexisting with commingling of paper and cardboard, glass, metal, and plastic.

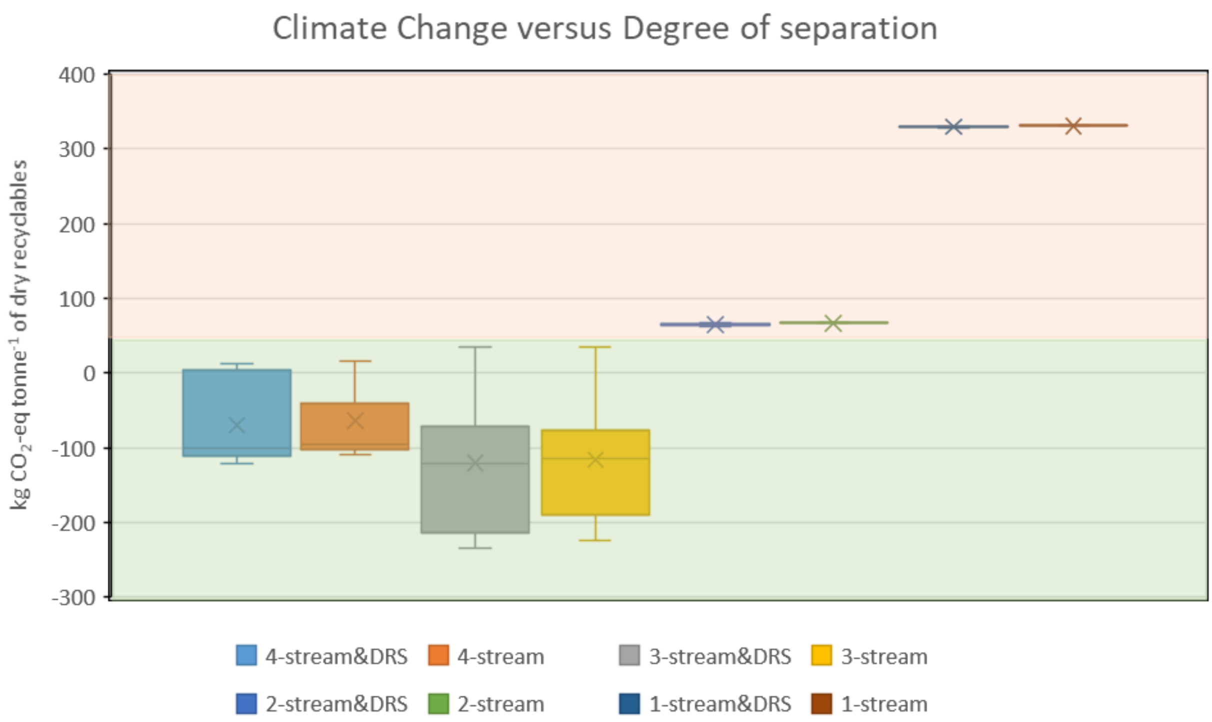


Figure 6: The box and whisker plot shows the distribution of the net results obtained for Climate Change (y-axis, expressed as kg CO_2-eq tonne^{-1} of dry recyclables). The area of the graph is divided in two indicating clustering of scenarios that proved to be beneficial (green shaded area) and clustering of scenarios that proved not to be beneficial (red shaded area).

4.3.1.1 Other environmental impact categories: summary

Annex A reports the complete list of results obtained for the remaining impact categories that, all in all, show a similar trend to Climate Change. The only one that shows a different trend is ionising radiation, which is greatly affected by the energy consumption and recovery of the system analysed (e.g. energy recovery at incinerator or energy consumption at recycling plants, depending upon the EU grid mix) and not so much by material recycling/recovery efficiencies.

4.3.2 Conventional costs

The total conventional costs represent the net cost of the waste management systems considered herein, including both expenses for any operation involved and revenues generated. The conventional costs have been further disaggregated into the three main ‘stages’ constituting the waste management system:

- Costs of collection, transport and sorting (i.e. all operations occurring prior to final recycling/reprocessing or incineration/landfilling).
- Costs of recycling and recovery material (including the costs related to recycling/reprocessing operations and the revenues obtained thanks to the production and sale of secondary materials).
- Costs of incineration and landfilling (including costs related to incinerating and landfilling residual waste and the revenues related to energy recovery thereof).

4.3.2.1 Costs of collection, transport and sorting

The collection, transport and sorting costs are displayed in Figure 7, which shows the relationship between collection, transport and sorting costs and the total recycling rate for dry recyclables (ranging from 9% to 49%). A linear regression was performed on the data (shown by the trendline in Figure 7), and the goodness-of-fit of it is calculated at 0.53, meaning that approx. 53% of variability observed in the target variable (i.e. the collection, transport and sorting costs) is explained by the regression model.

The trend observed in the results suggests that:

- Systems with a degree of separation of 3- or 4-stream generally have higher collection, transport and sorting costs.
- The increase in collection, transport, and sorting costs from lower to higher degree of separation is not disproportional. The increase is around 0-to-60 EUR per tonne of dry recyclables, corresponding to about 10 EUR per capita per year.

The clusters with the lowest collection, transport, and sorting costs are the 1-stream&DRS (DRS on glass bottles *and* DRS on metal cans *and* DRS on plastic bottles, and the joint effect of the three, coexisting with commingling of paper and cardboard, glass, metal, and plastic) and 1-stream (commingling of paper and cardboard, glass, metal, and plastic), where collection, transport and sorting costs are about 160-162 EUR tonne^{-1} of dry recyclables. By increasing the number of bins, Figure 7 shows that the both the total recycling rate and the total collection, transport and sorting costs increase. Specifically, the clustering of scenarios having the highest costs appears to be the 3-stream and, more specifically, the scenario with commingling of glass and metal coexisting with mono-stream collection of paper and cardboard, and plastic collected separately as mono-stream (216 EUR tonne^{-1} of dry recyclables).

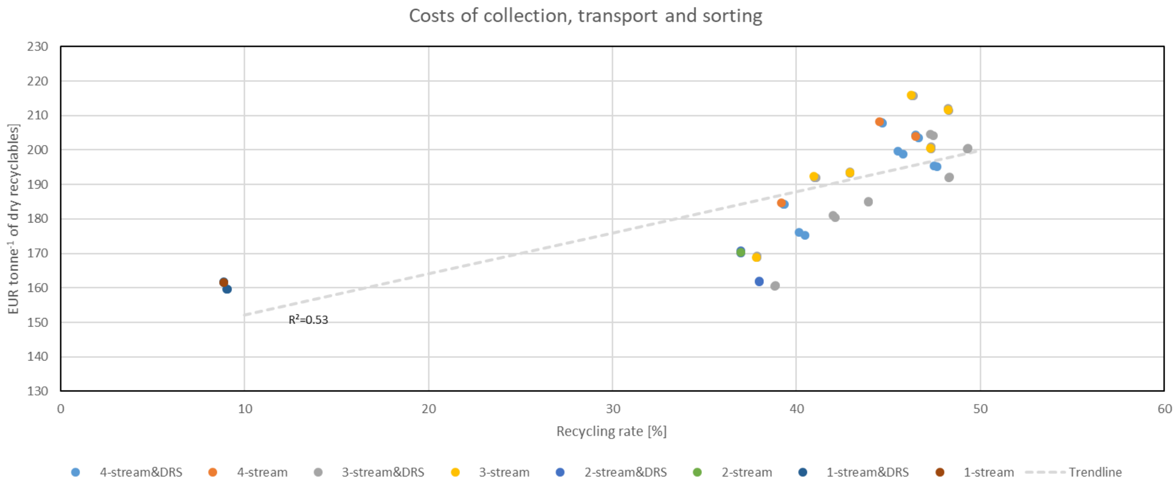


Figure 7. Costs of collection, transport and sorting (y-axis, expressed as EUR tonne^{-1} of dry recyclables) versus total recycling rate (x-axis, expressed as %). The linear trendline calculated based on the results is shown together with the related R^2 value.

4.3.2.2 Costs of recycling and material recovery

The recycling and material recovery costs are displayed in Figure 8, which shows the relationship between recycling and material recovery costs and the total recycling rate for dry recyclables (ranging from 9% to 49%). A linear regression was performed on the data (shown by the trendline in Figure 8), and the goodness-of-fit of it is calculated at 0.95 indicating a good fit of the linear regression with the data points.

The trend observed in the results suggests that:

- Systems with a degree of separation of 3-stream (3-bin) or 4-stream (4-bin) have overall higher net income as the revenues significantly overtake the costs for recycling, relative to systems with a lower degree of separation (or higher degree of commingling; i.e. 1- or 2-bin systems).
- There is no clear evidence that 4-bin systems achieve higher revenues than 3-bin systems. This tells that a certain degree of commingling is from a system-wide economic perspective desirable.
- Generally, the higher the recycling rate, the higher the net income for this stage (recycling/reprocessing) of the waste management system. At the same, time, point #1 still holds true, i.e. can't be said that that 4-stream systems achieve higher recycling rates than 3-stream.

The clusters with the highest costs (lower net income) are the 1-stream&DRS and 1-stream (DRS on glass bottles *and* DRS on metal cans *and* DRS on plastic bottles, and the joint effect of the three, coexisting with commingling of paper and cardboard, glass, metal, and plastic; commingling of paper and cardboard, glass, metal, and plastic; respectively) resulting in a total cost of -12 EUR tonne^{-1} of dry recyclables (or net income of 12 EUR tonne^{-1} of dry recyclables). The cluster of scenarios with the highest income was the 3-stream&DRS (and, specifically, the scenario with DRS on glass bottles, metal cans, plastic bottles coexisting with commingling of glass and metal, and commingling of plastic and beverage cartons) with a net income around 36-to-52 EUR tonne^{-1} of dry recyclables.

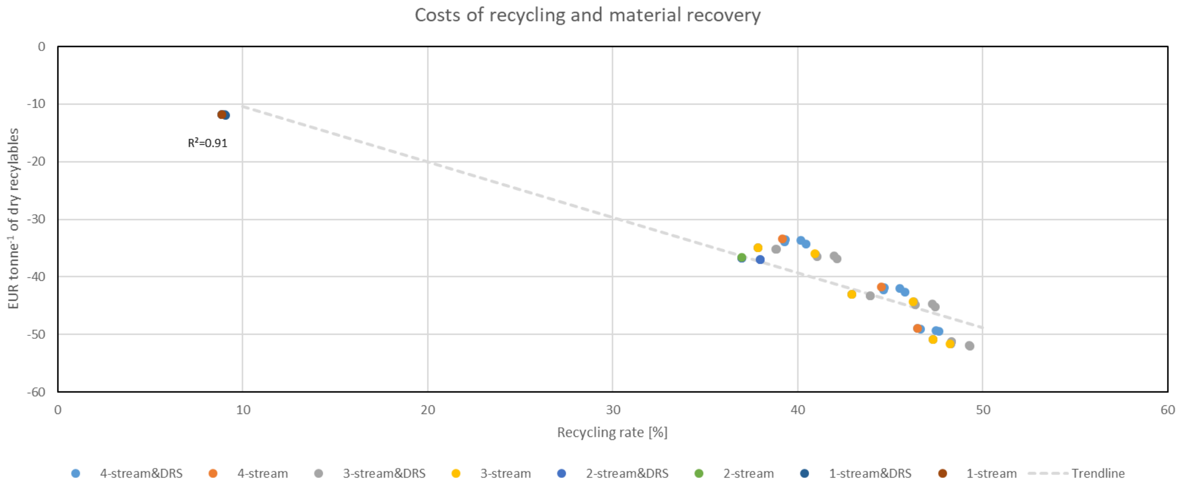


Figure 8. Costs of recycling and material recovery (y-axis, expressed as EUR tonne^{-1} of dry recyclables) versus total recycling rate (x-axis, expressed as %). Negative values indicate a net income (net income=costs–revenues; if revenues > costs, the result of the equation is negative). The linear trendline calculated based on the results is shown together with the related R^2 value.

4.3.2.3 Costs of incineration and landfilling

The incineration and landfill costs are displayed in Figure 9, which shows the relationship between incineration and landfill costs and the total recycling rate for dry recyclables (ranging from 9% to 49%). A linear regression was performed on the data (shown by the trendline in Figure 9), and the goodness-of-fit of it is calculated at 0.97 indicating a good fit of the linear regression with the data points.

The trend observed in the results suggests that the higher the number of bins, the higher the recycling rate, and the lower the incineration and landfill cost. This is explained by lower amounts of residual waste treated through incineration and landfill, as the recycling rates increase; however, still negative costs (i.e. a net income for this stage of the management system) occurs because residual waste is converted into energy entailing revenues which overtake treatment costs.

The clusters performing the worst (i.e. having higher costs per tonne of dry recyclables) are 1-stream&DRS and 1-stream (DRS on glass bottles *and* DRS on metal cans *and* DRS on plastic bottles, and the joint effect of the three, coexisting with commingling of paper and cardboard, glass, metal, and plastic; commingling of paper and cardboard, glass, metal, and plastic; respectively), resulting in a total cost of 26 EUR tonne^{-1} of dry recyclables. On the other hand, the cluster of scenarios performing the best are 4-stream&DRS (ranging from -12 to -2 EUR tonne^{-1} of dry recyclables) and, more specifically, the scenario having the lowest costs per tonne is the one where glass bottles are collected with a DRS coexisting with a mono-stream collection of paper and cardboard, glass, metal, and plastic, while beverage cartons are collected together with the residual waste.

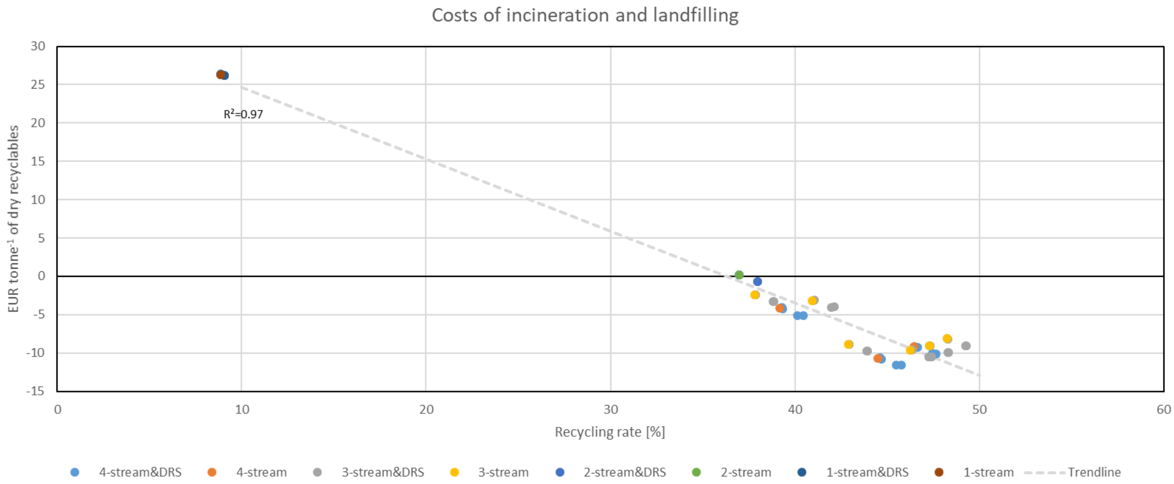


Figure 9. Costs of incineration and landfill (y-axis, expressed as EUR tonne^{-1} of dry recyclables) versus total recycling rate (x-axis, expressed as %). Note that revenues related to energy recovery are also included. The linear trendline calculated based on the results is shown together with the related R^2 value.

4.3.2.4 Total conventional costs

Figure 10 shows the relationship between net Total Conventional Costs and the total recycling rate for dry recyclables (ranging from 9% to 49%). A linear regression was performed on the data (shown by the trendline), and the goodness-of-fit of it is calculated as 0.37, meaning that approx. 40% of variability observed in the target variable (i.e. the net total conventional costs) is explained by the regression model.

The trend observed in the results suggests that:

- Systems with a degree of separation of 3 streams (3-bin) or 4 streams (4-bin) have overall significantly lower total costs than systems with a lower degree of separation (or higher degree of commingling; i.e. 1- or 2-bin systems).
- There is no clear evidence that 4-bin systems have overall lower total costs than 3-bin systems. This tells that a certain degree of commingling is, even from a system-wide economic perspective, acceptable and even desirable.
- Generally, the higher the recycling rate, the lower the total cost of the system.

Overall, the net Total Conventional Costs range from 122 to 176 EUR tonne^{-1} of dry recyclables. The clusters performing the worst are the 1-stream&DRS (DRS on glass bottles *and* DRS on metal cans *and* DRS on plastic bottles, and the joint effect of the three, coexisting with commingling of paper and cardboard, glass, metal, and plastic) and 1-stream (commingling of paper and cardboard, glass, metal, and plastic), where the net Total Conventional Costs was around from 174-176 EUR tonne^{-1} of dry recyclables. By increasing the number of separated streams (thus bins), the net Total Conventional Costs decrease while the total recycling rate increases, due to the higher recovery of recyclables and revenues obtained thereof. Specifically, the cluster performing the best appears to be the 3-stream&DRS and, more specifically, the scenario with DRS on glass bottles coexisting with commingling of paper and cardboard with beverage cartons, and metal with plastic performed the best (net total conventional costs of 122 EUR tonne^{-1} of dry recyclables).

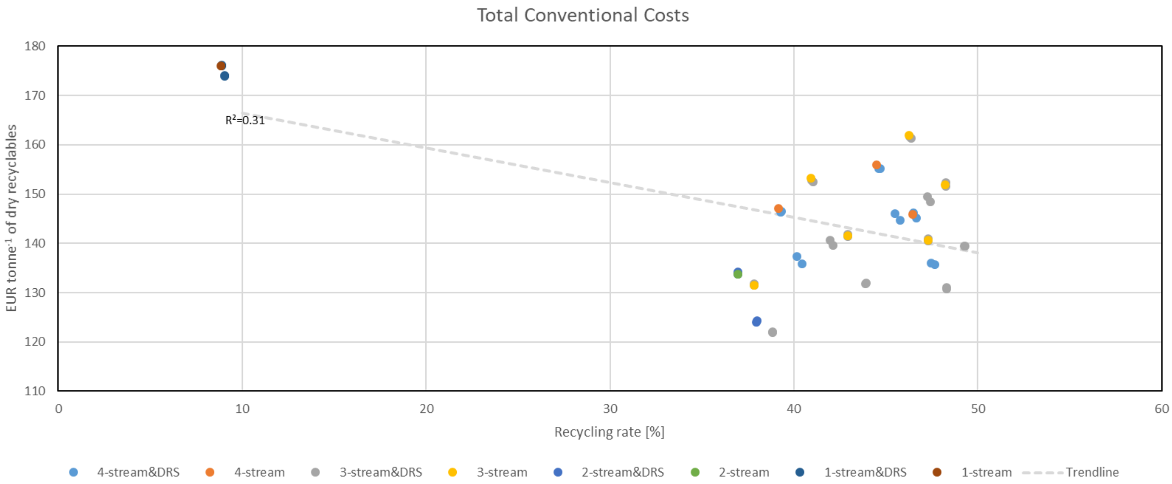


Figure 10. Total Conventional Costs (y-axis, expressed as EUR tonne^{-1} of dry recyclables) versus total recycling rate (x-axis, expressed as %). The linear trendline calculated based on the results is shown together with the related R^2 value.

The total conventional costs are mainly driven by collection, transport, and sorting costs (contributing by 76-83% depending upon the cluster), followed by recycling and material recovery costs (contributing by 6-20% depending upon the cluster), and, finally, incineration and landfill costs (contributing by 0.1-13% depending upon the cluster).

4.3.2.5 Costs per capita

The Total Conventional Costs are expressed as EUR per capita (EUR capita^{-1}) to illustrate the differences in costs for citizens when implementing different collection schemes (Figure 11, Figure 12). Here we present the total cost and the cost associated only with collection, transport, and sorting.

As it was observed in section 4.3.2.4, collection, transport and sorting costs contribute the most to the total conventional costs. Within the total conventional costs, from Figure 11 it can be observed that the higher the degree of separation, the higher the recycling rate and the collection, transport and sorting costs per capita that range from 28 to 38 EUR capita^{-1}. The results show that the clusters of 1-stream&DRS and 1-stream are the least expensive for citizens. However, one needs to remember that these costs only represent a part of the overall management system. The total picture, including the revenues from secondary material recovery, is shown in Figure 12 instead.

Figure 12 shows the relationship between the total conventional costs and the total recycling rate for dry recyclables (ranging from 9% to 49%). A linear regression was performed on the data (shown by the trendline in Figure 12), and the goodness-of-fit of it is calculated at 0.30, meaning that 30% of variability observed in the target variable (i.e. the total conventional costs) is explained by the regression model.

The trend observed in the results shows that systems with a degree of separation of 3- or 4-stream (3- and 4-bin) achieve overall lower total conventional costs while performing with higher recycling rates relative to 1- or 2-bin systems. The total conventional costs range between 22 EUR capita^{-1} (specifically, in the cluster 3-stream&DRS) and 31 EUR capita^{-1} (specifically, for the clusters 1-stream&DRS and 1-stream). Overall, for citizens is thus more expensive to have a single-stream collection as the revenues related to secondary materials are lower compared with scenarios where more recyclables are recovered (i.e., clusters characterised by a higher degree of separation).

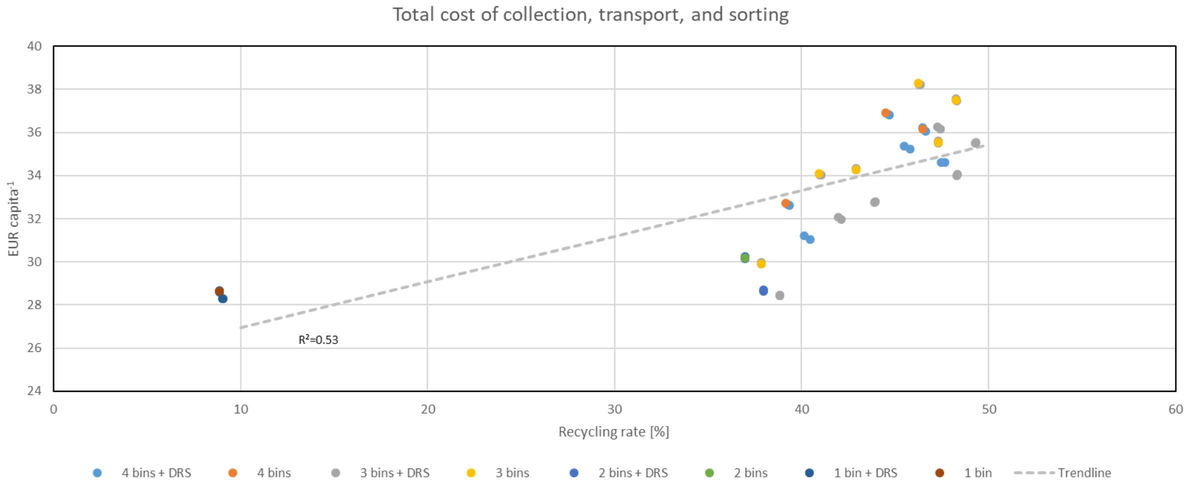


Figure 11. Total cost of collection, transport, and sorting (y-axis, expressed as EUR capita^{-1}) versus total recycling rate (x-axis, expressed as %). The linear trendline calculated based on the results is shown together with the related R^2 value.

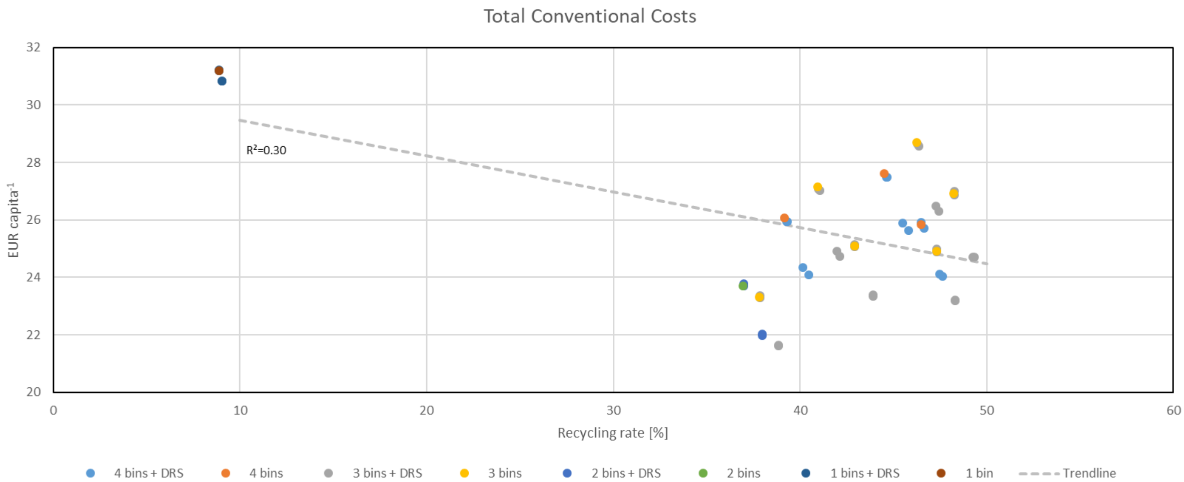


Figure 12. Total conventional costs (y-axis, expressed as EUR capita^{-1}) and total recycling rate (x-axis, expressed as %). The linear trendline calculated based on the results is shown together with the related R^2 value.

4.3.3 Societal costs (societal LCC or welfare assessment)

4.3.3.1 Externalities

The results obtained are displayed in Figure 13, where the externality costs are plotted against the total recycling rate for dry recyclables. A linear regression was performed on the data (shown by the trendline in Figure 13), and the goodness-of-fit of it is calculated at 0.76, meaning that approx. 76% of variability observed in the target variable (i.e. the externalities) is explained by the regression model.

The trend observed in the results shows that the higher the number of bins, the higher the recycling rate and the lower the cost of the externalities, following the trend observed for Climate Change (section 4.3.1). The externalities costs range between -45 EUR tonne^{-1} of dry recyclables (specifically, in the cluster 3-stream&DRS, specifically for the scenario where glass bottles, metal cans, and plastic bottles are subjected to a DRS, glass is commingled with metal, and plastic is commingled with beverage cartons) and 18 EUR tonne^{-1} of dry recyclables (specifically, for the clusters 1stream&DRS and 1-stream).

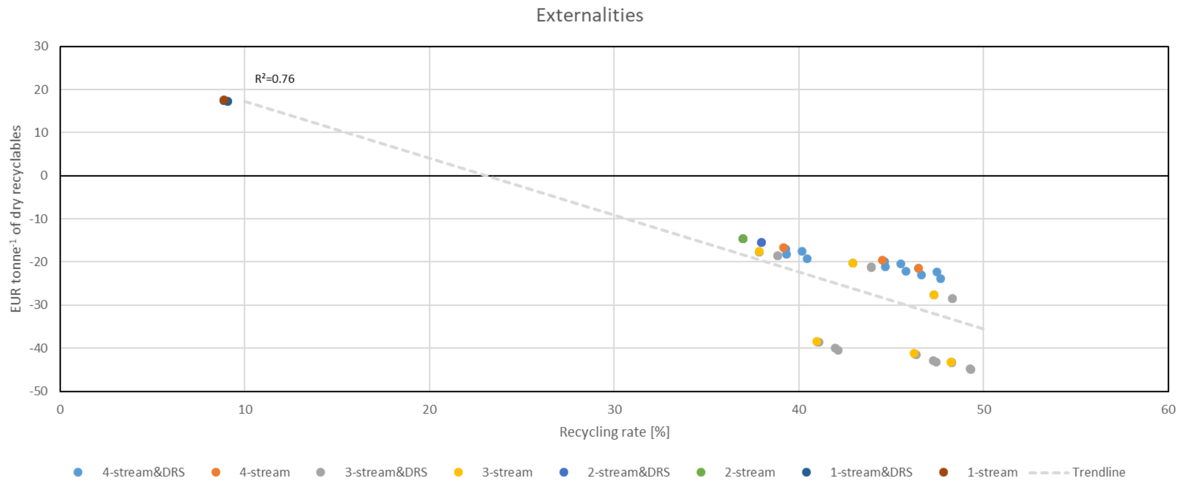


Figure 13. Externalities costs (y-axis, expressed as EUR tonne^{-1} of dry recyclables) versus total recycling rate (x-axis, expressed as %). The linear trendline calculated based on the results is shown together with the related R^2 value.

4.3.3.2 Total Societal Costs

By summing the Total Conventional Costs (excluding the non-already-internalized taxes included in the scenarios) and the Externalities costs, the Total Societal Costs are obtained.

Figure 14 shows the relationship between net Total Societal Costs and the total recycling rate for dry recyclables (ranging from 9% to 49%). A linear regression was performed on the data (shown by the trendline in Figure 14), while the goodness-of-fit of the regression is calculated at 0.80 indicating a fairly good fit.

The trend observed in the results suggests that the higher the number of bins, the higher the recycling rate, and the lower the Total Societal Costs. The clusters performing the worst are the 1-stream&DRS (DRS on glass bottles *and* DRS on metal cans *and* DRS on plastic bottles, and the joint effect of the three, coexisting with commingling of paper and cardboard, glass, metal, and plastic) and 1-stream (commingling of paper and cardboard, glass, metal, and plastic), where the Total Societal Costs range from 184 to 186 EUR tonne^{-1} of dry recyclables. By increasing the number of bins, it is clear from Figure 14 that the Total Societal Costs decrease and the total recycling rate increases, due to the higher recovery of recyclables. Specifically, the clustering of scenarios performing the best appears as 3-stream&DRS and, more specifically, the scenarios described by DRS on glass bottles, metal cans, and plastic bottles coexisting with commingling of glass and metal, and commingling of plastic and beverage cartons and DRS on glass bottles coexisting with commingling of glass and metal, and commingling of plastic and beverage cartons performed the best (total societal costs of 85 EUR tonne^{-1} of dry recyclables).

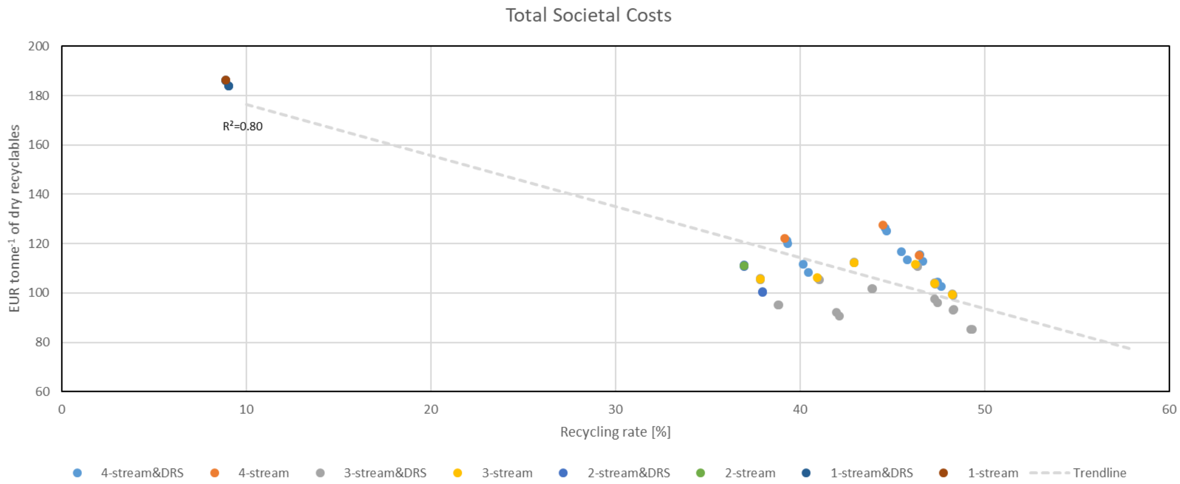


Figure 14. Total societal costs (y-axis, expressed as EUR tonne^{-1} of dry recyclables) versus total recycling rate (x-axis, expressed as %). The linear trendline calculated based on the results is shown together with the related R^2 value.

4.3.4 Employment

In Figure 15 the net results obtained for Employment are plotted via a box and whisker plot against the degree of separation. The span of each box represents the interquartile range, which represents where 50% of the results lay. The interquartile range is calculated as the difference between the third quartile (upper end of the box, which represents the value under which 75% of the results are found) and the first quartile (lower end of the box, which represents the value under which 25% of the results are found). The box plot is shown together with the upper (where the end indicates the maximum result) and lower (where the end indicates the minimum result) whiskers, the median net result (horizontal line within the each box), and the average net result (cross within each box) (Figure 15).

Figure 15 shows that the scenarios generating more employment are those with 3-stream and 3-stream&DRS, followed by 4-stream and 4-stream&DRS. On the other hand, the scenarios with the lowest employment are 1-stream&DRS, 1-stream, followed by 2-stream&DRS and 2-stream, as these scenarios are characterised by high levels of commingling, low collection rates, and low recycling rates.

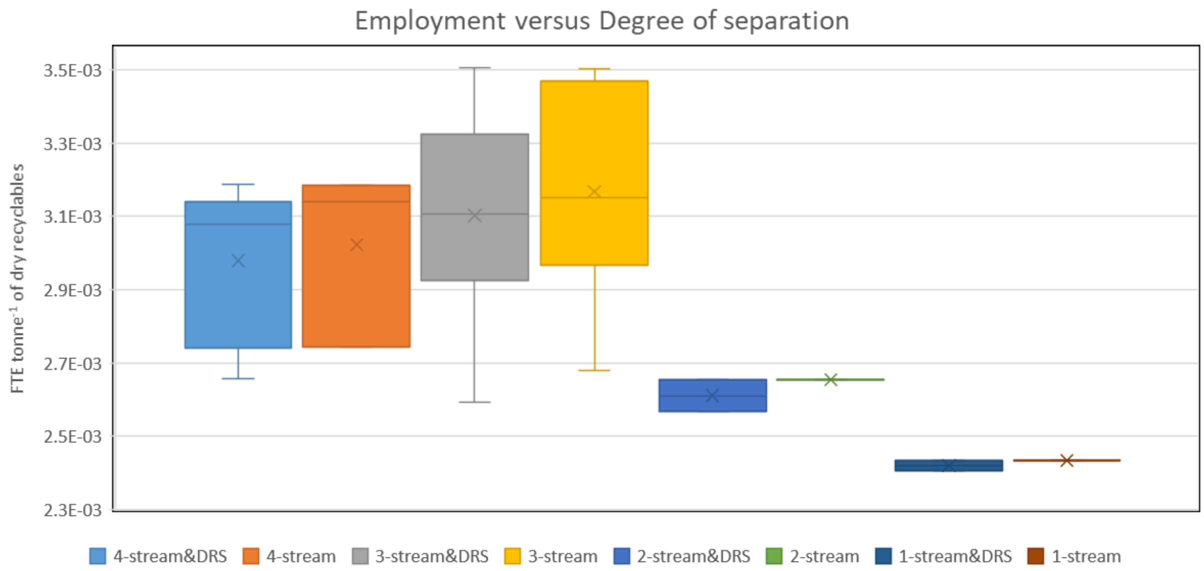


Figure 15. Box and whisker plot representing the total employment (y-axis, expressed as FTE tonne^{-1} of dry recyclables) against the different degrees of separation.

4.3.5 Sensitivity analyses

The results obtained for Climate Change for the sensitivity analysis performed on the collection rate of plastic (i.e. "SA1" in Figure 16) and on the addition of an advanced sorting of mixed residual waste (i.e. "SA2" in Figure 16) are compared (individually) against the results obtained for the default scenarios (i.e. "D" in Figure 16) via a box and whisker plot.

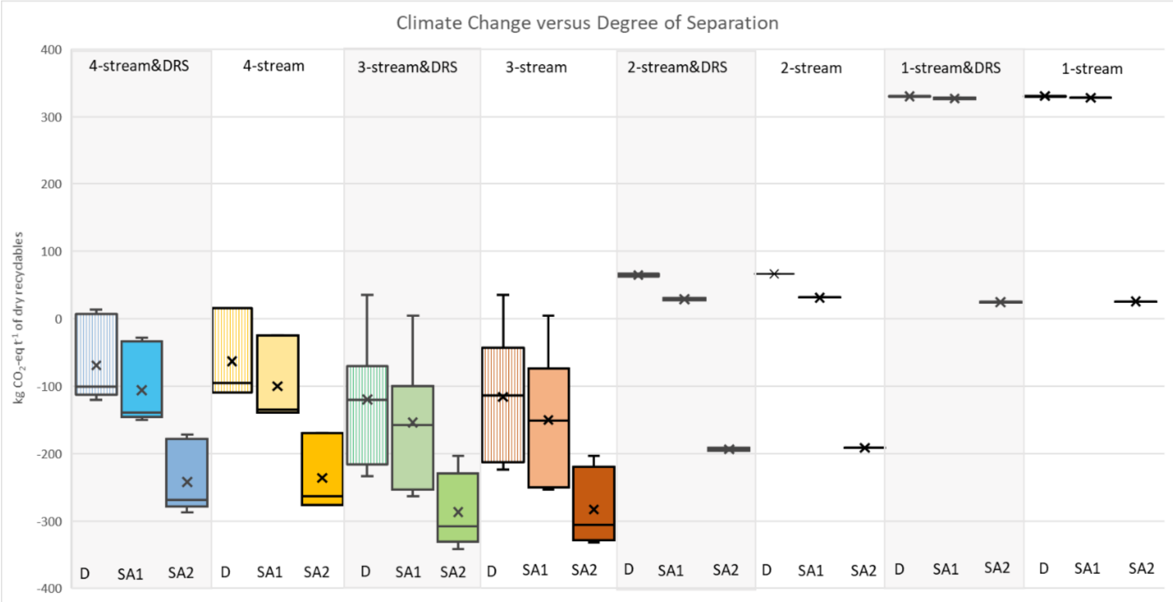


Figure 16. Box and whisker plot representing the Climate Change impacts (y-axis, expressed as kgCO_2-eq t^{-1} of dry recyclables) against the different degrees of separation for the default scenarios ("D"), the sensitivity analysis performed on the collection rates of plastic ("SA1"), and the sensitivity analysis performed on the advanced sorting of residual waste ("SA2").

Figure 16 shows that the same trend in the results as for D is observed for SA1 and SA2. Indeed, 3-stream and 3-stream&DRS scenarios perform as the ones contributing with the highest net savings, followed by 4-stream and 4-stream&DRS, 2-stream and 2-stream&DRS, while the ones performing the worst are the 1-stream&DRS and 1-stream scenarios.

When comparing the results of D with SA1, it is clear that increasing the collection rate of plastic comes with additional savings as less plastic is directed to incineration and more is recycled (Figure 16), all in all decreasing GHG emissions and thus Climate Change impact.

When comparing the results of D with SA2, Figure 16 shows that the net savings at a system-wide level considerably increase when establishing a sorting prior to incineration/landfilling of residual waste. This allows to recover additional material that would have otherwise been lost, especially metals and plastic, which recycling incurs important GHG benefits. Yet, this should not be seen as a competing scheme to recycling, but, on the contrary, as an additional and complementary management stage. This can be derived by the fact that 1- or 2-stream systems complemented with centralised sorting of mixed waste never achieve better performances on Climate Change than 3- or 4-stream systems complemented with centralised sorting of mixed waste . The same result is valid in general for the other impact categories. In a nutshell, sorting of the residual waste plays the role of increasing total recovery and savings thereof, but it is not in general a substitute for separate collection at source.

4.4 Limitations of the study

The limitations of this study have been identified as follows:

- The data availability for collection rates and impurities level for certain commingling setups was incomplete or missing and, therefore, other potential combinations have been excluded from this analysis (e.g. commingling of glass, metal, and plastic).
- The data availability for employment at the collection stage was scarce. For paper and cardboard collection, glass collection, metal collection, plastic collection, and residual waste collection, the employment was based on the share of labour cost on the total cost as reported in (Utilitalia & Bain,

2018). Further, the cost of commingled waste collection was assumed to be the same for all commingling setups assessed, as data availability was limited. As for the other waste streams, the employment of commingled collection was based on the share of labour cost on the total cost as reported in (Utilitalia & Bain, 2018).

- Interviews with operators highlighted that the implementation of DRS would consistently affect them as a substantial part of valuable material (e.g. PET bottles, metals cans), which are today associated with significant revenues, would be lost to the advantage of deposit-refund-system operators. The implementation of DRS would thus represent for them i) a material loss, but also ii) an economic loss that should be accounted for in a broader cost-benefit assessment, via distributional impact analysis, which is not herein performed. Such an assessment would need to take into account that investments have already been made by operators based on the 'current system' (without DRS). Therefore, by enforcing DRS on valuable materials, the amortisation of such investments would be slower (due to the loss of input per year) and operators' revenues would decrease due to the reduced amount of valuable materials available to them.
- In this assessment, the shadow price relative to time spent at home to segregate waste has not been accounted for in the societal life cycle costing and externalities.
- Finally, in the current assessment, the difference in convenience for citizens to have 4-, 3-, 2-, or 1-stream collection (that might – or might not – correspond to having 4, 3, 2, or 1 additional bin) has not been accounted for as this was outside the scope of the analysis. We highlight below some of the considerations that might be taken into account in a further analysis of these effects in follow-up work.

Box 2. The limits of separate collection: 'separation fatigue' and optimum separation efficiency

Is there an optimum level of waste separation?

Until recent years, the trend towards separate collection has been unidirectional: in the overwhelming majority of contexts, separation had been lagging behind objectives and represented a key limiting factor in increasing e.g. the quantity and quality of recycling. Most municipalities – and most countries at an aggregated level – are struggling to deploy adequate levels of separate waste collection in order to comply with recycling targets.

In a few specific contexts and among some front-running systems in waste collection and management however, a novel question may be arising, which is that of the *limit* to sorting and separation, or reaching diminishing returns in how many fractions citizens are asked to separate.

As illustrated above, while there are drastic improvements in moving from 1 to 2 waste flows, these start reducing with a high number of fractions (above 3). When weighing in the other factors advocating against an ever-more refined separation system, the question of an optimum, rather than maximum, level of separation can arise.

As pointed above, this present study did not take into account the 'shadow' or hidden cost of separation at the household level, which may become significant as the numbers of separate fractions increase. These would arise from:

a) the 'shadow' time spent by households to learn about the sorting schemes in place and actually carry out the sorting and disposal; and

b) the space limitations of maintaining a variety of containers, which might come at a premium especially in urban settings with high real-estate costs or other space constraints.

The hidden cost for citizens (a) should also take into consideration behavioural factors, and 'separation fatigue', i.e. there is only so much time and attention that even environmentally-conscious citizens can dedicate to sorting waste.

For instance, this phenomenon has been taken into account in the city of Amsterdam[11], where some plastics (e.g. not under DRS) are to be disposed of in the residual waste, or in some regions of Norway (cf. also the alternative approach detailed in section 3.2.1.3).

[11] https://www.amsterdam.nl/en/waste-recycling/household-waste/what-goes-each-container/

However, it is important to stress that only few places where waste separation is already very advanced can even consider this type of tradeoff: most municipalities across Europe still need to make considerable progress and increase levels of separation (both in terms of the number of fractions collected, and in terms of overall quantities and qualities of separately collected waste) in order to progress towards e.g. forthcoming recycling targets. Notably, this regards the separate collection at the source of bio-waste and paper and cardboard.

5 Conclusions and recommendations for dry recyclables collection

5.1 Main conclusion

The evidence obtained via life cycle assessment and costing performed on fifty-five management scenarios reflecting the possible variations of commingling systems for dry recyclables across the EU indicates that:

- Systems with a degree of separation of 3 streams or 4 streams perform significantly better than systems with a lower degree of separation (or higher degree of commingling; i.e. single- or dual-stream systems) environmentally.
- There is no clear evidence that 4-stream systems perform better than 3-stream systems, neither environmentally nor economically. This tells that such degree of commingling (3-stream) is acceptable and does not seem to lead to detrimental environmental and socio-economic effects compared to systems with a higher degree of separation.
- Single-stream collection (1-stream) of dry recyclables achieves the worst environmental performance across all the impact categories considered in the assessment, followed by dual-stream (2-stream) systems. This holds true even when accompanied by deposit-refund-scheme (DRS) on selected material fractions such as glass bottles, metal cans, and PET bottles.
- Single-stream collection (1-stream) of dry recyclables achieves the worst economic performance (conventional costs) and the worst socio-economic performance (societal costs). This is due to the reduction of secondary material recovery relative to systems with a higher degree of separation (or less commingling). This holds true even when they are accompanied by deposit-refund-scheme (DRS) on selected material fractions such as glass bottles, metal cans, and PET bottles.
- Systems with 3- and 4-stream incur higher collection, sorting and transport conventional costs but overall less total conventional costs at a system-wide level relative to single-stream systems, thanks to the revenues from secondary materials. The same applies to the total societal costs. Instead, when compared against dual-stream systems, the ranking is not as neat because dual-stream have competitive costs and the environmental performance gap is not as pronounced as for single-stream.
- Generally, the higher the recycling rate, the lower the net Climate Change impact of the waste management system.
- Commingling of glass with plastic waste, especially flexible, is not a recommendable practice in general because of the contamination of the plastic streams with glass fines and dust.

5.2 Noncompliant practices

Based on the evidence built via collection of data and subsequent modelling in this study, it appears that single-stream commingling systems overall achieve significantly worse environmental, economic and socio-economic performance compared with systems with higher degree of separation, notably, 3- or 4-stream systems. A similar conclusion applies to dual-stream systems with respect to the environmental dimension, although the environmental performance gap relative to 3- or 4-stream system is not as pronounced as for single-stream systems.

Based on our analysis and considering Article 10, paragraph 2 of the Waste Framework Directive, as amended by EC 2018/851, it therefore appears that commingling of all dry recyclables in a single-stream clearly leads to detrimental environmental effects while increasing (economic and socio-economic) waste management costs at a system-wide level, taking into account the costs of waste collection and treatment as well as revenues from sales of secondary raw materials. In other words, these single-stream schemes lead to higher costs for citizens, when accounting for the entire life cycle of the waste and not only for segments of it. On this basis, the results of this study suggest that single-stream commingling practices should be considered as noncompliant and not allowed as possible derogations from Article 10.

A similar conclusion can be extended to dual-stream systems, as they show systematically lower environmental performances than 3- or 4-stream systems. However, for dual-stream systems, the environmental gap with 3- or 4-stream systems is not as pronounced as that of single-stream and their lower conventional costs somehow mitigate their total societal impact (which is the sum of conventional costs and monetised environmental impacts).

5.3 Best practices

Within this study we define best practices those systems with the best performance on Climate Change, as this shows a great correspondence with the recycling rate. Both climate change mitigation and increased recycling rate are main objectives of the EU Green Deal and Circular Economy Action Plan. From this perspective, the best commingling scenarios were 3-stream systems; more specifically, the best performance in terms of Climate Change were achieved in the following cases:

- Commingling glass with metal; commingling plastic with beverage cartons; separate collection of paper and cardboard (3-stream).
- Commingling glass with metal; separate collection of paper and cardboard; separate collection of plastic (3-stream).
- Commingling metal with plastic and beverage cartons; separate collection of paper and cardboard; separate collection of glass (3-stream).

The above are further improved with DRS, notably if DRS is simultaneously applied to glass bottles, PET bottles, and metal cans. These configurations are then followed by other combinations of 4-stream and 3-stream systems, notably:

- Commingling plastic with beverage cartons; the remaining fractions individually collected (4-stream).
- Commingling paper and cardboard with beverage cartons; commingling glass with metals; separate collection of plastic (3-stream).
- Separate collection of all streams (beverage cartons go with the residual waste) (4-stream).
- Commingling metals with plastic; separate collection of paper and cardboard; separate collection of glass (beverage cartons go with the residual waste) (3-stream).
- Commingling paper and cardboard with beverage cartons; the remaining fractions individually collected (4-stream)
- Commingling paper and cardboard with beverage cartons; commingling metals with plastic; separate collection of glass (3-stream).

The literature review conducted in the course of this project (Joint Research Centre of the European Commission, 2023) and different consultations with waste collection operators indicated that commingling of glass with plastic waste is in general not ideal because of the contamination of plastic waste with glass fines and dust.

The inclusion of centralized plants (here exemplified with a sensitivity analysis called "advanced sorting of mixed residual waste") for further recovery of materials from the residual waste (i.e. waste not captured by separate collection at source) improves the overall waste management system performance for both 3- and 4-stream systems, thanks to the additional recovery of materials. However, our findings also indicate that such centralized sorting plants for mixed residual waste should not be considered, in general, as an alternative to separate collection at source, but rather as a complement or add-on.

Our analysis also illustrate that achieving improved collection and recycling rates for plastic waste is key to reducing the EU waste management impact on Climate Change. Currently, a significant portion of the uncollected plastic waste currently ends up incinerated. A diversion of plastic waste to recycling incurs indeed two simultaneous and cumulative benefits relative to the *status quo*: i) it avoids GHG emissions at incinerators (where it otherwise would partly end up) *and* ii) it avoids GHG emissions associated with primary plastic production (that would otherwise have to be produced, *ceteris paribus*).

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List of abbreviations and definitions – see also section 2.1

BC	Beverage Carton waste
BOF	Basic Oxygen Furnace
CAPEX	Capital Expenditures
CLCC	Conventional Life Cycle Costing
DRS	Deposit Refund System (or Scheme)
EAF	Electric Arc Furnace
EC	European Commission
ECS	Eddy Current System
EEA	European Environment Agency
EU	European Union
EWR	Early Warning Reports
GL	Glass waste
HDPE	High-Density Polyethylene
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LDPE	Low-Density Polyethylene
MBT	Mechanical-Biological Treatment
ML	Metal waste
MRF	Material Recovery Facility (sorting plant)
MSW	Municipal Solid Waste (= 'Municipal Waste' as per WFD definition)
MT	Metal waste
NIR	Near-Infrared sensor
OCC	Old Corrugated Cardboard
OPEX	Operational Expenditures
PC	Plastic and Cardboard waste
PE	Polyethylene
PET	Polyethylene Terephthalate
PL	Plastic waste
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinylchloride
SLCC	Societal Life Cycle Costing
SWC	Separate Waste Collection
WFD	Waste Framework Directive (European)

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Annexes

Annex A. Spreadsheet-file containing the data used for modelling as well as additional results not presented in this report.

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