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Impacts of the collection and treatment of dry recyclables

Commingling practices and their environmental and economic impacts: an analysis based on life-cycle assessment and life-cycle costing

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Contents

Abstract

This study focuses on the separation, collection and subsequent management of the dry recyclable fractions (i.e. beverage cartons, glass, metal, paper and cardboard, and plastic) of municipal waste in the EU-27. The goal of the study is to recommend compliant/noncompliant and, in general, best commingling practices for the separate collection of dry recyclables in view of the obligations set by the EU Waste Framework Directive and its upcoming revision. To this end, the study first identifies the most relevant collection and commingling practices for dry recyclables around the EU-27 and subsequently assesses the environmental and economic impacts of 65 different management practices with a view to providing evidence-based recommendations for the interpretation and, ultimately, revision of the EU Waste Framework Directive, with a special focus on the derogations from a strict separate collection of the recyclables. The results indicate that single-stream collection (commingling all dry recyclables together) incurs detrimental environmental and economic effects and should be avoided. Systems with three or four streams achieve comparable environmental and economic performances and are recommended, together with selected dual-stream systems where glass, metal and plastic are commingled, while paper and cardboard are collected in a separate stream or commingled with beverage cartons. There is no evidence that four-stream systems are better than three-stream systems or dual-stream systems when paper and cardboard are kept separate from the other light dry recyclables, suggesting that some degree of commingling can be safely accepted and even recommended in view of the potential benefits of reducing the overall number of streams collected (costs, space, convenience), although these were not assessed quantitatively in this study.

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Executive summary

Policy context

Directive 2008/98/EC (Waste Framework Directive), as amended by Directive (EU) 2018/851 (Article 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 (MS) may allow derogations from this provision provided that some conditions are met. These conditions relate to demonstrating that: i) collecting certain types of waste together does not affect their potential to undergo preparation 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 EU-27. From such an 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 a low share and weight of the total, e.g. metal), but also simply to poor collection practices.

Key conclusions

The evidence obtained via life cycle assessment and costing performed on 65 management scenarios, reflecting the main variations of commingling systems for dry recyclables across the EU, indicates the following:

- Systems with a degree of separation of three or four streams in general perform better than systems with a lower degree of separation (or higher degree of commingling, i.e. single- or dual-stream systems) environmentally. Results obtained for a specific configuration of dual-stream system, namely commingling of glass, metal and plastic while collecting paper and cardboard as a separate-stream or commingled with beverage cartons, show similar performances to three- and four-stream systems.
- There is no clear evidence that four-stream systems perform better than three- or dual-stream (the latter under the condition that glass is commingled with metal and plastic, while paper and cardboard is collected as a separate-stream or commingled with beverage cartons) systems, either environmentally or economically. This would suggest that a degree of commingling of three or two streams, under certain conditions, is acceptable and does not lead to detrimental environmental and economic effects compared to systems with a higher degree of separation.
- Single-stream collection of dry recyclables achieves the worst environmental performance across all the impact categories considered in the assessment, followed by dual-stream systems when paper and cardboard is commingled with metal, plastic, and beverage cartons. This holds true even when these systems are accompanied by a deposit refund scheme (DRS) for selected material fractions such as glass bottles, metal cans and PET bottles.
- Single-stream collection of dry recyclables achieves the worst economic performance. 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 these systems are accompanied by a deposit refund scheme (DRS) for selected material fractions such as glass bottles, metal cans and PET bottles.
- Systems with three and four streams incur higher collection, sorting and transport costs but less overall costs at the system-wide level relative to single-stream systems, thanks to the revenues from

[1] 'Separate collection' refers to waste streams being collected separately by type and nature so as to facilitate a specific treatment.

secondary materials. The same applies to the full environmental costs[2]. However when compared with dual-stream systems, the ranking is not as neat because dual-stream systems have competitive internal costs and the external cost gap is not as significant as for single-stream systems.

- Centralised sorting plants for residual waste[3] should be complementary to separate collection at source and have the potential to improve the overall waste management system performance under prerequisites such as separate collection of bio-waste, paper and cardboard, and metal/glass drinks containers. In other words, these plants should be seen as additions to already advanced or well-functioning separate collection systems whose economic cost and environmental and social impacts have been assessed (e.g. impacts would be the net sum of burdens and savings incurred by installing these plants, as compared to a counterfactual system that does not include these plants).
- Generally, the higher the recycling rate, the lower the net Climate Change impact of the waste management system, i.e. a high correlation exists between these two indicators.

Related and future JRC work

This study is part of a larger project supporting the delivery of the second Circular Economy Action Plan (CEAP Administrative Agreement I between the JRC and DG ENV) which contains a number of work packages related to the impact assessment of distinct actions, namely: 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 (to which this study belongs). In relation to the latter, additional outputs are foreseen in particular on waste bin labelling harmonisation and quality management systems in waste management.

Quick guide

This report starts with a general policy background (Section 2) and a description of the collection practices in place across the EU-27 (Section 3). This is followed by a description of the assessment methodology applied and the results (Section 4). The final recommendations are presented in Section 5.

[2] In this study, when we refer simply to '*costs*', we mean *environmental life cycle costs* (internal costs plus environmental taxes, e.g. landfill and incineration taxes); meanwhile, when we refer to '*full environmental costs*', we mean internal costs plus external costs (external costs = monetised environmental emissions).

[3] The residual mixed waste is the portion of the generated waste (in this case, the generated dry recyclables) that is not captured by separate collection at source.

1 Introduction

Policy context

Directive 2008/98/EC, as amended by Directive (EU) 2018/851, and commonly known as the 'EU Waste Framework Directive' (WFD), regulates the management of waste across EU Member States (MS). The Directive, in its Article 10, states that 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 some conditions are met. These conditions relate to demonstrating that: i) collecting certain types of waste together does not affect their potential to undergo preparation 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 scientific and techno-economic studies and preliminary evidence from EU monitoring exercises (such as the Early Warning Reports by the EEA; European Environment Agency, 2023) seem to indicate that in the vast majority of 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

The JRC has undertaken this study on behalf of DG ENV to assess the current status of dry recyclables collection (among others, of commingling practices) across the EU and the environmental and economic implications. The study is part of an Administrative Agreement with DG ENV. 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 municipal waste (MW). To fulfil this goal, the study first identifies the most relevant collection practices for dry recyclables across the EU-27 and subsequently assesses the environmental and economic impacts of such practices with a view to 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 waste management (such as transportation, sorting, recycling and any other treatment) up until the final recovery or disposal of the waste .

The conclusions and recommendations from this study can be used in the context of the application and, ultimately, 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 MW.

[4] see footnote 1.

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 by Directive (EU) 2018/851 (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 MW (municipal 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**' refers to waste streams being collected 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 to 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*, preparation for re-use, recycling and backfilling.

'**Preparation 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 of 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**’: means the quotient of mass between the quantity of waste separated at source (including impurities that unintendedly end up with it) and the quantity of the same waste generated (%) (e.g. glass waste separately collected out of total glass waste generated).

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

‘**Degree of separation**’: The clustering of the scenarios based on the number of streams for recyclables (e.g. separate-streams, dual-stream, etc.). This is also known (conversely) as ‘Degree of commingling’ (the higher the degree of separation, the lower the 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 two-stream)**’: Here meant as dividing dry recyclables into two separate streams, generally one rich in fibre and one rich in container-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[5].

‘**Separate-streams collection**’: Here meant as separate collection of each of the dry recyclables by nature and type, strictly in line with the WFD.

‘**Impurity rate**’: It is defined as 100% minus the purity rate; it represents the percentage of non-*target material* in a given waste stream (e.g. per cent 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 (%).

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

‘Residual waste’ (also known as mixed residual waste or mixed waste): The stream of municipal 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 one-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 material recovery facility (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), here we 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.

[5] We are aware that in some cases sorting plants run by a Producer Responsibility Organisation (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 an 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 'List of abbreviations and definitions' section 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 (EU) 2018/851, states that (paragraph 1, Article 10) 'Member States shall take the necessary measures to ensure that waste undergoes preparation for re-use, recycling or other recovery operations…'. Paragraph 2, Article 10 states that 'Where necessary to comply with such obligations [those of paragraph 1, Art. 10] and to facilitate or improve preparation for re-use, recycling and other recovery operations, **waste shall be subject to separate collection**[6] **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 preparation 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.

Article 10, as amended by Directive (EU) 2018/851, further states that Member States shall regularly review derogations under that paragraph taking into account good practices in separate collection of waste and other developments in waste management.

Upon reading paragraph 2, Article 10 of Directive 2008/98/EC (Waste Framework Directive) as amended in Directive (EU) 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 practised 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 MW along with their low specific weight (as collected) would incur disproportionate economic costs for their individual collection and sorting. Furthermore, separation of metals from other materials is relatively easy using 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 EU-27. From such an analysis it is evident that in the vast majority of 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, Article 10. The state-of-play of the commingling practices across the EU-27 MS is illustrated in Section 3.

[6] 'Separate collection' means the collection where a waste stream is kept separate 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; 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 legislation, etc.) and external (i.e. geographical, socio-demographic, and economic) factors that need to be taken into account when designing them (Albizzati et al., 2023a). 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 carried out by the EEA included a survey filled out by Member States to have a clear state-of-play on the economic instruments used, legal instruments, etc., and also provided a qualitative overview of the collection schemes in place indicating which are the dominant ones for different waste streams. This also accounted for the urbanisation level (i.e. cities, towns and suburbs, and rural areas) and the collection systems (either door-to-door, or bring collection points, or civic amenity sites) that affect capture rates and the quality of the collected waste. Based on the qualitative information provided in the Early Warning Reports, 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 carton waste), and we also identified a set of the most common commingling systems which are as follows:

- plastic, metal, beverage cartons;
- paper and cardboard, plastic, metal, beverage cartons;
- metal, plastic;
- paper and cardboard, glass, metal, plastic;
- paper and cardboard, beverage cartons.

However, our estimation at EU level excluded other commingling setups that exist at Member State level, such as i) glass, metal; ii) plastic, beverage cartons; iii) glass, metal, plastic; iv) paper and cardboard, plastic, metal. Moreover, 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 Reports also looked into the deployment of deposit refund schemes (DRS), whether on a voluntary or mandatory basis, and on what materials they are implemented (e.g. glass bottles, plastic bottles). By combining the information provided in the Early Warning Reports and the country-specific reports of FEVE[7], it was possible to further identify which countries currently have a DRS in place, on what materials, and its coverage. Specifically, the countries identified as having an established DRS are Sweden, Finland, Estonia, Lithuania, Denmark, the Netherlands, Germany and Croatia. The details of such an analysis can be consulted in Albizzati et al. (2023b).

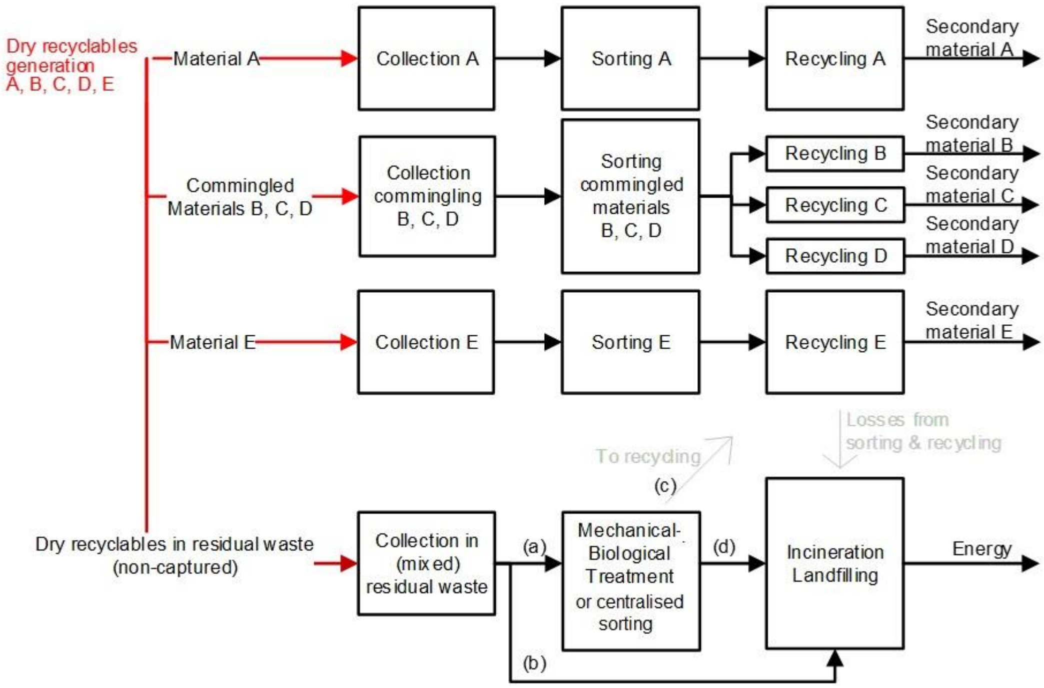
3.2 Further process steps and ultimate fate of collected fractions

The waste collected at the source of generation 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', abbreviated as 'MRF', or selection plants) where bales of targeted material fractions are produced. Such a 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 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 waste 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

[7] FEVE is the Federation of European manufacturers of glass containers for food and beverage and flacons for perfumery, cosmetics and pharmacy markets; see https://feve.org/about-us/feve/

plastic waste stream, are compacted, baled and sent to a further sorting plant (or line in the same facility) for further sorting (for example, 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, the quality of which is often dependent on the output quality of the collection scheme in place.

Depending on the success rate of the source separation by households and commercial services, a share of the recyclables generated ends up in the residual waste (in literature referred often to as 'mixed waste' or 'mixed residual waste') that is ultimately disposed of in landfills or incinerated for energy recovery. In some cases, the 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 residual waste contains a significant share of organic waste (note that even though a separate collection of organic waste is in place, organic waste is still present in the 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, materials A and E are collected separately, i.e. individually, while B, C and D are commingled. Downstream operations involve sorting and recycling. The uncaptured dry recyclables are collected together with the residual waste and sent to further treatment. This can be via centralised sorting or MBT[8] (a; 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 for landfilling or incineration (d; Figure 1).



NB: In this example, materials A and E are collected separately, i.e. individually, while B, C and D are commingled. Downstream operations involve sorting and recycling. The uncaptured dry recyclables are collected together with the residual waste and sent to further treatment. This can be via (a) centralised sorting or MBT or (b) direct incineration/landfilling. From the residual waste sorting, a part of the output may further undergo recycling (c) and a part will be destined for landfilling or incineration (d).

Figure 1. Exemplary illustration of a typical waste management scheme for management of dry recyclables.

3.2.1 Sorting of dry recyclables (material recovery facilities)

Sorting plants (also called material recovery facilities – MRFs – or selection plants) can be configured with different equipment and machines depending on the composition of the input-waste to be managed. This is

[8] 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".

very much dependent on the collection system in place. According to 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 (e.g. one-bin).
- Sorting plants for **dual-stream (or twin-stream) commingled** waste, i.e. for a collection system where dry recyclables are divided into two streams (e.g. two-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 stream 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 (e.g. three-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 separate-material streams of glass and paper/cardboard.

It should be kept in mind that other variations of these archetypes exist, 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 instead of being commingled with other containers (e.g. in Denmark until recently). 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 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 reported to be applied in many regions of the UK and the US as well as in some areas of the EU-27 (e.g. Greece). The collected recyclables are unloaded from trucks in 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 75 mm, separates the 'fines', which contain most of the broken glass material. The second section, with a cut-off of 160x170 mm, 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.

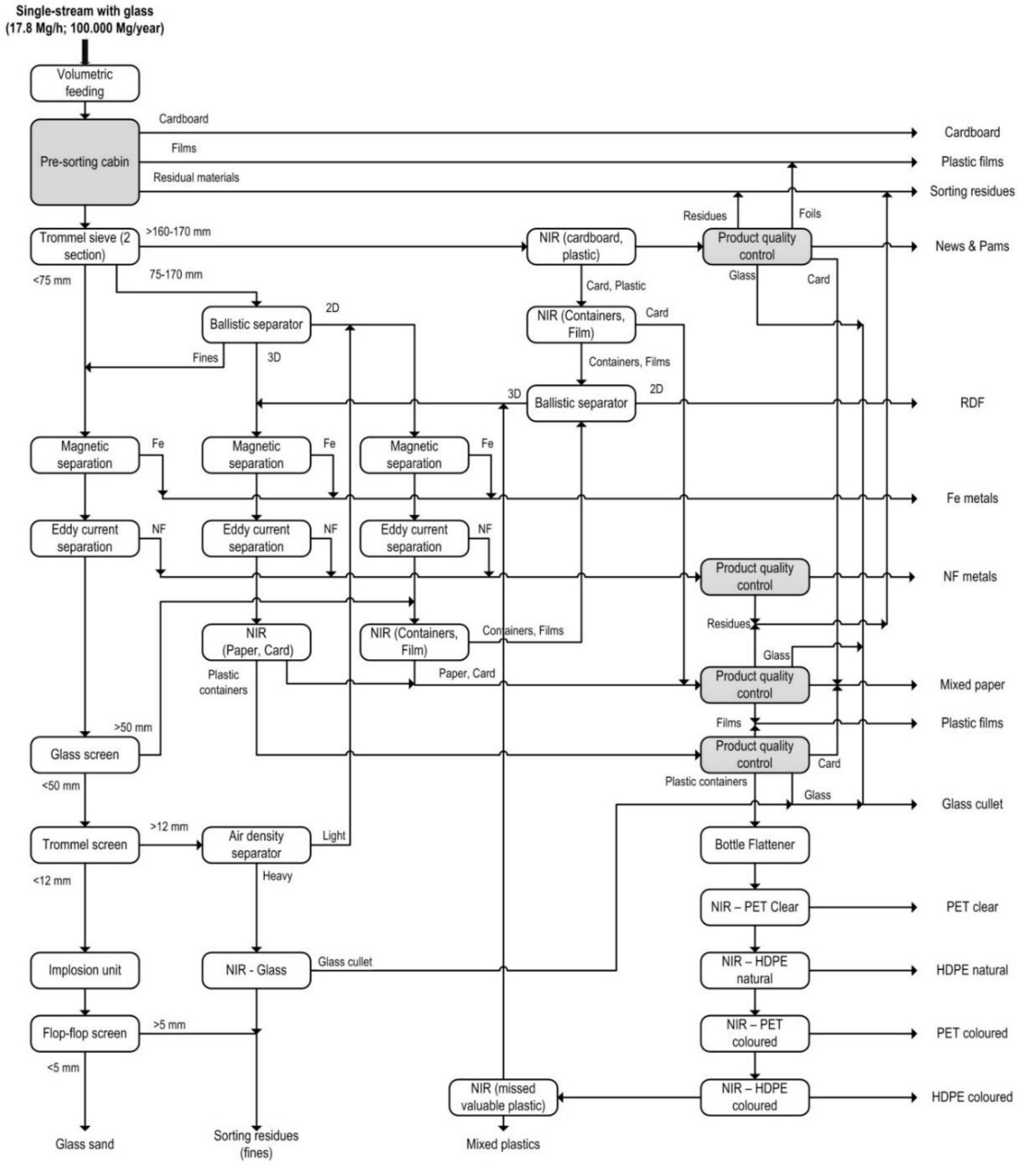
At this point there are four material streams which will be processed on individual lines:

- 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 then joins the 2D (flat) 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 sorter 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, which are then recirculated to the beginning of the 3D line.

- The fines line has the main objective of producing a clean glass cullet product (>12 mm). This is achieved with a sequence of separation and cleaning processes, including screening, air density separation and final NIR sorting for removal of contaminants.

In contrast to 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.



NB: Arrows represent conveyor belts. OCC: old corrugated cardboard; HDPE: high-density polyethylene; PET: polyethylene terephthalate; News & Pams: Newspapers, Periodicals and Magazines; RDF: Refuse-derived fuel. Taken from Cimpan et al. (2015).

Figure 2. Example of sorting plant (material recovery facility) managing a single-stream commingled input of glass, metal, paper and cardboard, and plastic.

3.2.1.2 Sorting plant for lightweight packaging

An example of a 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 into two to four further particle size intervals, with the last cut-off used for fine grain material, typically <20 mm (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 the input stream). NIR sensor sorting is then used to remove beverage cartons (also called liquid carton containers). 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 typically constitute a mixed polymer product; however, another sensor unit can be used to pick up remaining/missed valuable 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 of 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 to changes of the volumetric flow in the plant setup. In spite of the high level of automation, most of these systems need to be supported with additional manual quality control.

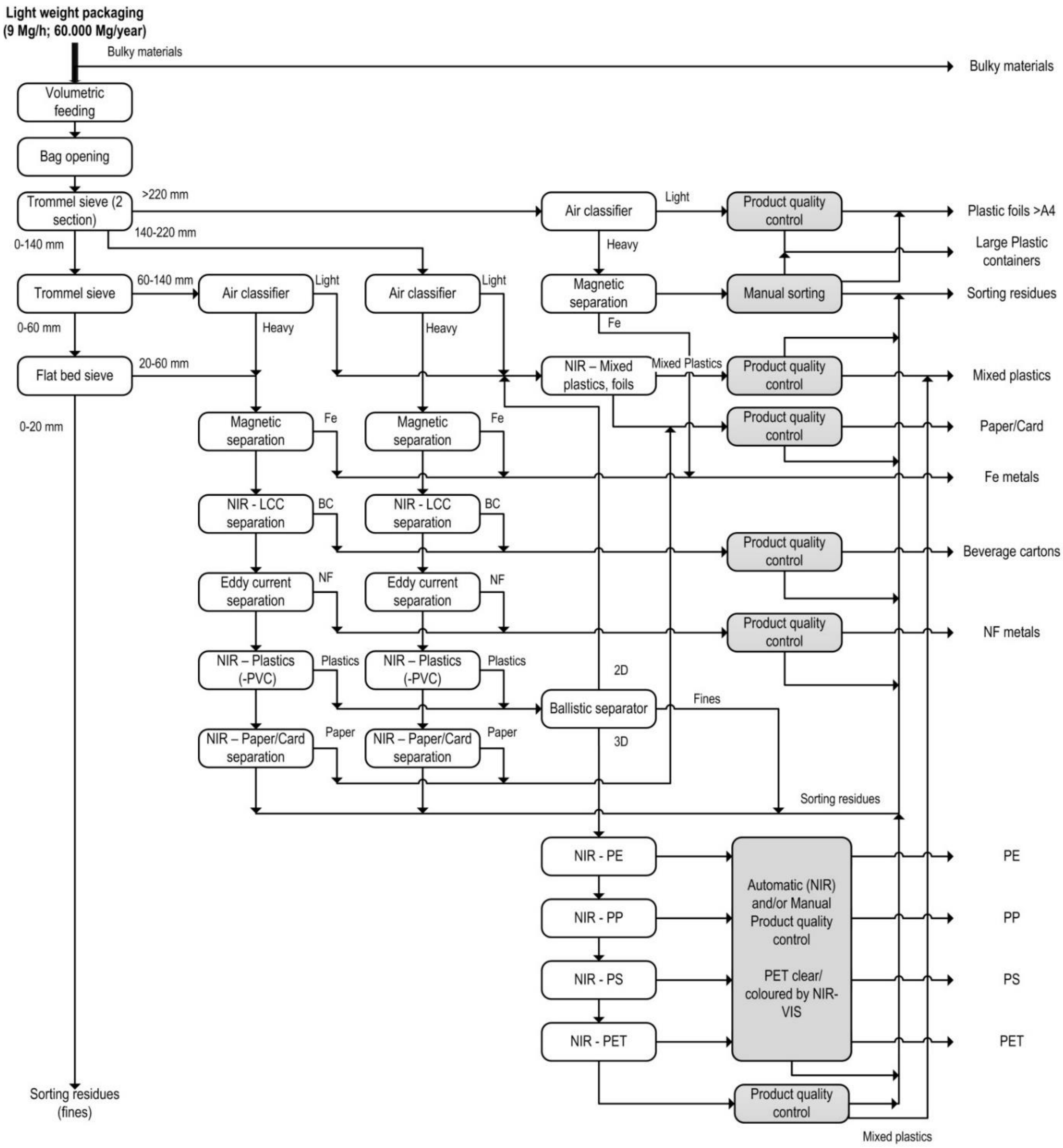


Figure 3. Example of sorting plant for lightweight packaging, i.e. managing an input of light packaging composed of plastic, metal, and beverage cartons (including other composite).

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. Insights from operators in the field of collection and sorting in relation to commingling

Interview with HUB Ambiente Srl operators

1. Commingling of glass with plastic waste

According to the company, commingling glass with plastic waste is not ideal for the following reasons, mainly related to implications at the subsequent sorting plant:

- 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/machinery at the 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 with other recyclables

Beverage cartons can be commingled with paper and cardboard, or in a 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 a specific sensor for separation, as they are not waste treatment plants. Also, the aluminium and polymeric fractions may not be 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, EUR 250-300 k). This has high amortisation costs 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 in other EU Member States).

3. Commingling of metal waste

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

- The separation of metal waste via magnets and an eddy current system (ECS) makes separation feasible and efficient both from a mix of plastic, beverage cartons and metals, and from a mix of metal and glass waste.

3.2.1.3 Advanced sorting systems: (additional) recyclables recovery from residual 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[9], whereby some plastics are collected along with (and subsequently sorted from) residual 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 and cardboard) or through a DRS (e.g. metal and glass drinks containers).

- Residual 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 relevant in high-wage economies).

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

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

It should be stressed that this system, characterised by an advanced sorting of the residual waste, is not alternative to separate collection but rather complementary. Indeed, one should notice that most of the waste is still separately collected at the source, notably bio-waste, paper and cardboard and metal/glass drinks containers, which altogether make up about 60% of the generated MW. The main difference, therefore, regards the management of the total plastic waste (around 10% of the generated MW), which is *partly* recovered from the residual waste instead of being fully separately collected or commingled with other waste fractions (e.g. with metals and beverage cartons). We use the word '*partly*' because the Norwegian system also has a DRS for PET bottles, thus a fraction of the plastic waste generated is actually already separately collected via the DRS. The complementarity offered by the advanced sorting plant for the residual waste also lies in the fact that such centralised sorting enables the recovery of additional material (e.g. metals) from the residual 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. Then, 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 into 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 an indefinite number of times.

3.2.2.2 Recycling of metal waste

The reprocessing of steel is typically carried out via electric arc furnace (EAF) or basic oxygen furnace (BOF) (Damgaard et al., 2009). Prior to the EAF or BOF, pre-treatment (sorting) operations take place to remove unwanted items. The BOF process accepts only 25–30% steel scrap, while the EAF process accepts 100% steel scrap and is where the majority of 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 in later steps in order to conserve energy (and optionally additional fossil energy can be added). Next, the scrap is loaded into 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 deoxidising 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 MW, (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 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 ways of reprocessing 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, also includes de-inking to brighten up the pulp for use in higher value paper grades such as printing and copy paper for which such a 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, 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) divide 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 remelted. 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; pelletising; and, quenching (water cooling to granulate the plastic and sell it as a final product) (Al-Salem et al., 2009). The focus of the present document and modelling is on mechanical recycling, as chemical recycling currently deals 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 (around 72.5%), polymer (around 24%) and aluminium (around 3.5%) (Zero Waste Europe, 2020). Due to their composite nature, beverage cartons cannot be easily recycled by paper mills that recycle regular paper-based packaging, as the latter has too short a delamination process that would not allow a correct separation of all layers of the 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[10].

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

4 Environmental and socioeconomic impacts 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 waste management in the EU-27. The LCA has been carried out in accordance with the guidelines of the ISO 14040/14044 standards (ISO, 2006a, 2006b). It should be underlined that the methodology and the inventory data used in this study largely build on the waste management assessment model developed by the authors and detailed in parallel publications (Albizzati et al. (2023a), Albizzati et al. (2023c)). 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. (2023a).

To address the performance of collection schemes in the modelling, we focus the modelling on the following key 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 (also known as 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 therefore include 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 EU-27 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 EU-27, 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 Reports, 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 carton waste. Note that waste management encompasses different processes, and a number of products arise from the exploitation of the waste, notably recyclates, heat and 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 separate-streams or commingled in different ways. To cover the possible combinations, we assess a total of **65 scenarios** which are illustrated in Table 1.

Notice that beverage cartons are either commingled (displayed) or directly disposed of with the residual waste (not displayed) as this seems to still be a practice in many regions across the EU. Notice also that **the residual waste bin and bio-waste bin are not included** in the number of bins and are thus not displayed in Table 1. However, they are part of the overall MW collection system. So, if the reader wants to know the total number of bins a household will have, they should simply add '+2' to the bins displayed for dry recyclables, as we assume these two to be separately collected as separate-streams in line with the obligations of the WFD[11].

The scenarios assessed cover the most common commingling systems in the EU-27 that we identified (as described in Section 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:

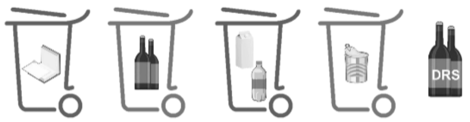
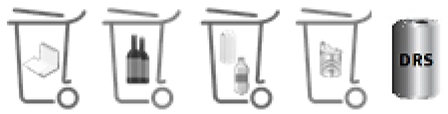
- all separate streams for each dry recyclable (separate-stream separation);
- commingling of plastic, metal, beverage cartons;
- commingling of paper and cardboard, plastic, metal, beverage cartons;
- commingling of metal, plastic;
- commingling of paper and cardboard, glass, metal, plastic;
- commingling of paper and cardboard, beverage cartons;
- commingling of glass, metal;
- commingling of plastic, beverage cartons;
- commingling of glass, metal, plastic;
- combination of different commingling systems;
- DRS on glass bottles, plastic bottles, and metal cans.

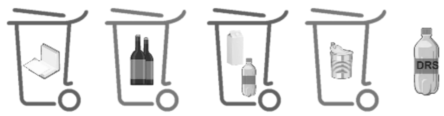
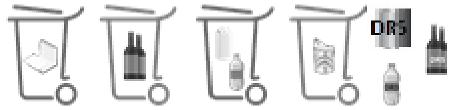
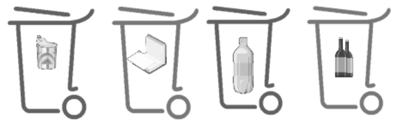
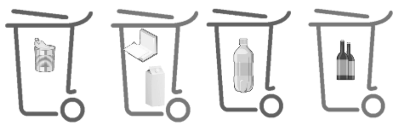
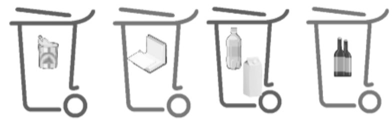
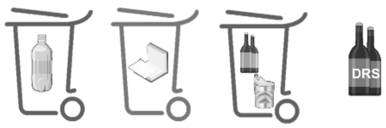
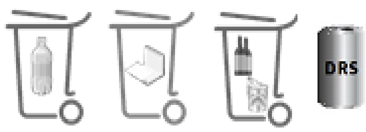
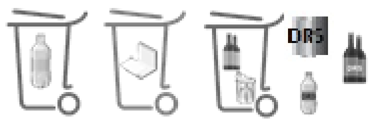
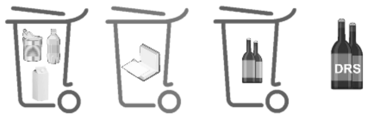
Table 1. List and description of scenarios considered in the analysis.

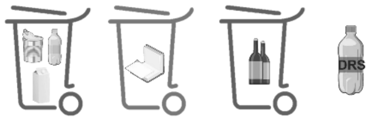
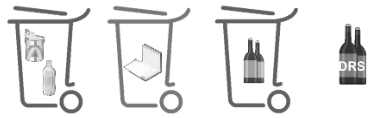
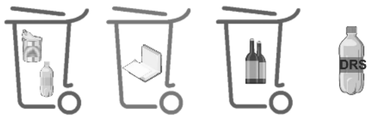
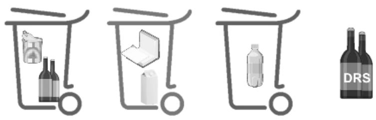
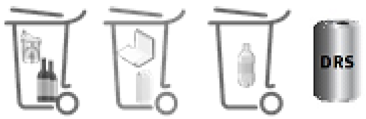
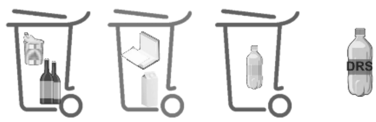
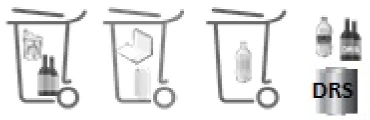
NB: Each bin represents a collected stream. The counting on the number of streams excludes the fact that there are two additional streams to be collected (residual waste and bio-waste). The following acronyms are used: "BC" waste beverage cartons; "DRS" deposit refund scheme; "GL" glass waste; "PC" paper and cardboard waste; "PL" plastic waste; "MT" metal waste. Commingling is indicated in 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.

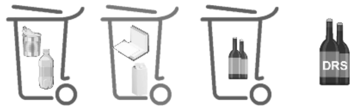
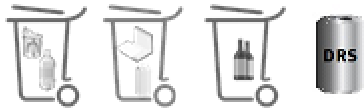
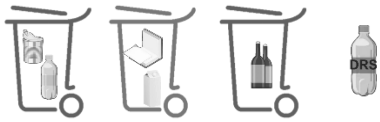
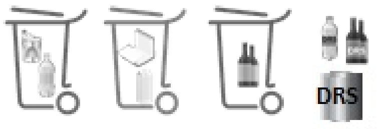
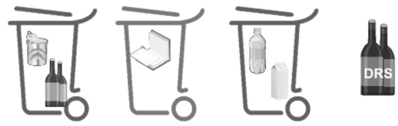
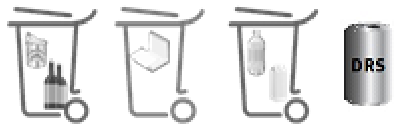
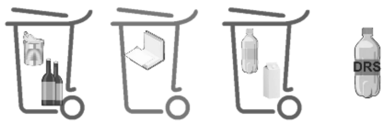
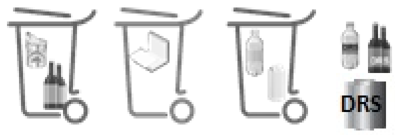
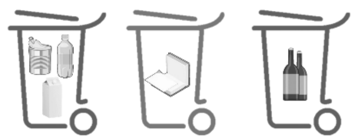
<table>
<tr><th colspan="7">Legend</th></tr>
<tr><td>Paper and cardboard waste
</td><td colspan="2">Glass waste
</td><td>Metal waste
</td><td colspan="2">Plastic waste
</td><td>Beverage carton waste
</td></tr>
<tr><td colspan="2">DRS for glass bottles
</td><td colspan="3">DRS for plastic bottles
</td><td colspan="2">DRS for metal cans
</td></tr>
<tr><th>System (No. of streams)</th><th colspan="4">Acronym of scenario</th><th colspan="2">Description</th></tr>
</table>

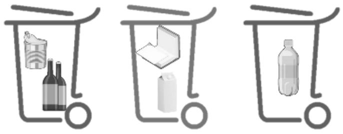
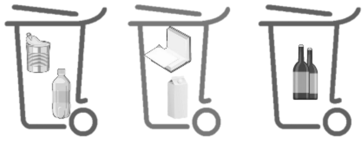
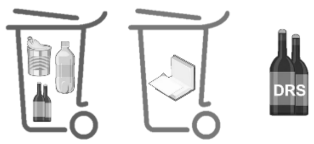
[11] From 2024 in the case of separate collection of bio-waste.

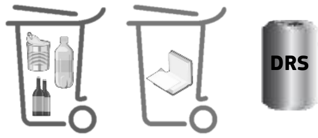
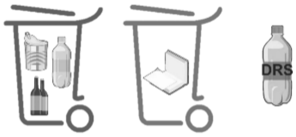
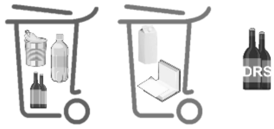
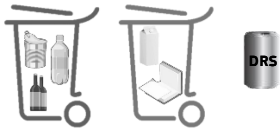
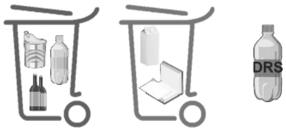
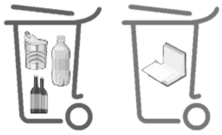
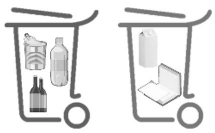
4-stream&DRS	DRS GL & all separate streams	
	DRS MT & all separate streams	
	DRS PL & all separate streams	
	DRS & all separate streams	
	DRS GL & (PC + BC)	
	DRS MT & (PC + BC)	
	DRS PL & (PC + BC)	
	DRS PL, MT, GL & (PC + BC)	
	DRS GL & (PL + BC)	
	DRS MT & (PL + BC)	

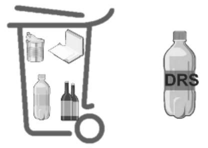
	DRS PL & (PL + BC)	
	DRS PL, MT, GL & (PL + BC)	
4-stream	All separate streams	
	(PC + BC)	
	(PL + BC)	
3-stream&DRS	DRS GL & (GL + MT)	
	DRS MT & (GL + MT)	
	DRS PL & (GL + MT)	
	DRS PL, MT, GL & (GL + MT)	
	DRS GL & (MT + PL + BC)	

	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)	
	DRS GL & (GL + MT + PL)	

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

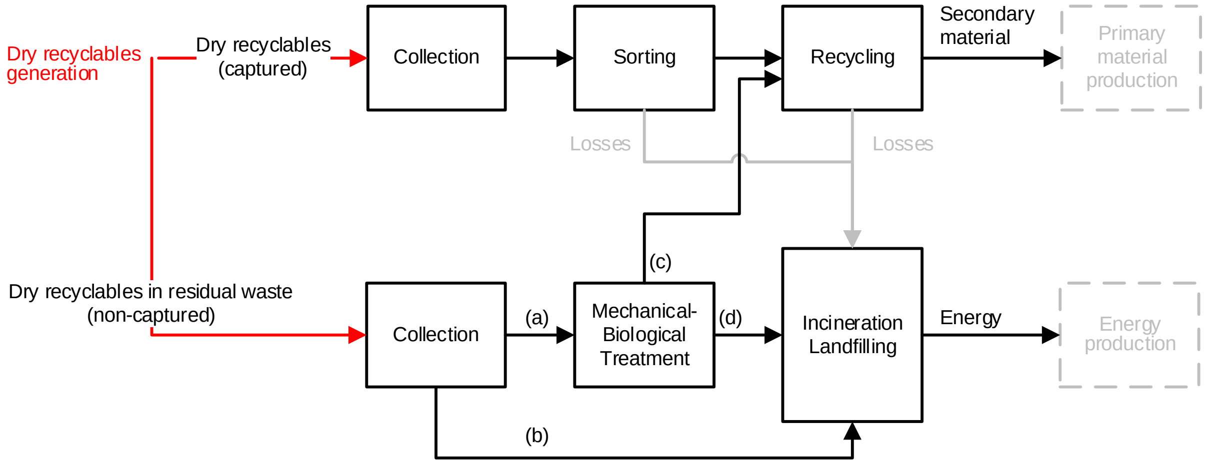
4.1.3 System boundaries

The system boundary includes all the operations involved in the life cycle of the waste once this is generated, i.e. separation at the source, 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 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 "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 be the same across all scenarios anyway, 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 in addition to the main service strictly consisting of 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 in the course of 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 EU-27) 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 to that 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. (2023a) 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's JRC (GECO reports; Keramidas et al., 2018, and subsequent updates).



NB: 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 residual waste sorting can be sent to partly recycling (c) and partly incineration and landfilling (d), depending on the sorting plant material recovery rates. Boxes with a solid black outline indicate induced processes, while boxes with a grey dashed outline indicate avoided processes (substitution of energy and virgin material, i.e. credits for waste exploitation) following the so-called system expansion approach (ISO, 2006a, 2006b).

Figure 4. Generic system boundary for the LCA of dry recyclable waste management.

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 captured in the scope of this specific study. Each stage of the waste management system was modelled in the dedicated waste-LCA model EASETECH 3.4.0 (Astrup et al., 2012; Clavreul et al., 2014) 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 does not have a direct influence. 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 et al., (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. Note that for both 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. (2023a) was applied. Note that recycling of paper is based on ecoinvent processes, while steel recycling is based on PEF processes. For more information the reader is referred to Albizzati et al, (2023a) and Albizzati et al. (2023b).

4.1.5 Sensitivity analyses

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

- The material recovery rates of sorting plants for commingled waste are changed according to primary data obtained from an Italian sorting facility located in the North-East of Italy. The facility analysed presents higher sorting rates for plastic, but lower ones for aluminium compared to the ones considered in the baseline (see details in Annex A).
- The capture rate of plastic waste, which is very poor on average according to the literature 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 highest collection rate assumed across the scenarios, which corresponds to that of commingling plastic together with glass and metal based on the primary data provided by an Italian waste collection company located in the North-East of Italy.
- Inclusion of a centralised sorting of residual waste prior to its incineration and landfill to recover additional recyclables from the residual waste. This is done by modelling an average sorting plant for the EU based on the data collected by Montejo et al. (2013). Note however that those data do not originate from an advanced centralised sorting plant, but rather more basic MBT plants. Results show that it is beneficial to have a centralised plant treating residual waste (even when this is a simple MBT), even more so with advanced sorting technology. Centralised separation is therefore a useful complement to separation at source.

The aim of these sensitivity analyses is to show the influence of sorting plant efficiencies, plastic recovery and additional centralised material recovery from residual waste in terms of recycling rates and environmental impacts (especially climate change and resource depletion).

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 MW 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) and Martinez-Sanchez et al. (2015). The LCC shares the same subject, 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 speaking, *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 sake 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). Note that these include prices for air/soil/water emissions but not for disamenities such as nuisance, noise, odour, congestion, time spent or other similar social effects. Notice that any externality priced in (e.g. in the 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 *environmental LCC* (eLCC)[12] describes the financial cost and environmental costs (e.g. CO_2 taxes that are expected to be implemented, landfill and incineration tax; based on the definition of Hoogmartens et al. (2014). The *full environmental LCC* (feLCC)[13] sums the internal costs to the monetised environmental emissions that are currently non-internalised (based on the definition of Hoogmartens et al., 2014), both expressed as shadow prices[14].

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 Euros as of year 2020 price

[12] Note that in previous publications, the authors have referred to the *environmental LCC* as *conventional LCC* (CLCC).

[13] Note that in previous publications, the authors have referred to the *full environmental LCC* as *societal LCC* (SLCC).

[14] In the eLCC, budget costs are accounted for in "factor prices" (market prices excluding transfers). Internal costs are then the sum of budget costs expressed as factor prices (market prices) plus transfers. Instead, budget costs in the feLCC 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 in the feLCC 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 feLCC) is equal to the internal costs price (of the eLCC), which implies assuming perfect market conditions. This approach was also taken in recent life cycle costing studies, e.g. Albizzati et al. (2021).

levels, henceforth noted EUR_{2020}, unless otherwise indicated. 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.

For the specific shadow price of CO_2 we used the updated figure suggested by CE Delft and DG MOVE for 2030, i.e. EUR_{2016} 100 per tonne CO_2 which is recommended as a default value, with a minimum-maximum range of EUR_{2016} 60-189 per tonne CO_2 (van Essen et al., 2019). The remaining internal costs (based on literature) and external prices (using the report from 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)).

4.2.2 Key cost inventory and assumptions

The unit costs (EUR_{2020} per 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 waste management may be found in Albizzati et al. (2023c).

4.2.3 Estimation of employment

The total employment induced by the waste management system is also quantified as an additional indicator, as proposed in Taelman et al. (2020). 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 recyclables 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 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. Positive net results reflect burdens on climate change, whereas negative results (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 exploitation 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 8% 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 0.87, thus indicating a fairly good fit of the linear regression with the data points.

The trend observed in the results suggests the following:

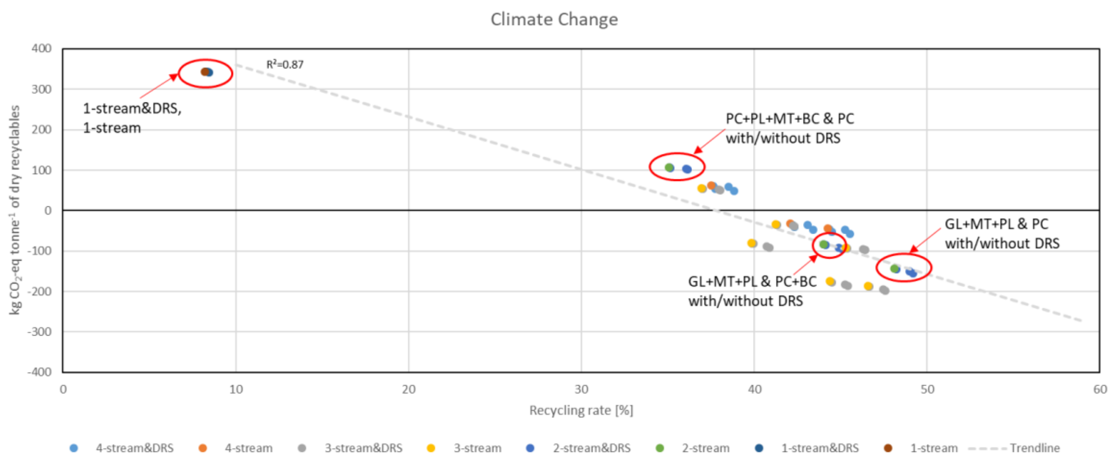
- Systems with a degree of separation of three or four streams generally perform better than systems with a lower degree of separation (or higher degree of commingling; i.e. single- or dual-stream systems, the latter under the condition that paper and cardboard are commingled together with light dry recyclables, i.e. metal, plastic, beverage cartons). Results obtained for one specific configuration of dual-stream system, namely commingling of glass, metal and plastic while collecting paper and cardboard as a separate-stream or commingled with beverage cartons, show similar performances to three- and four-stream systems.
- There is no clear evidence that four-stream systems perform better than three-stream systems or two-bin systems, the latter under the condition that glass, metal and plastic are commingled, while

paper and cardboard are either collected separately or together with beverage cartons. This reveals that **a certain degree of commingling is acceptable and does not lead to detrimental environmental effects** compared to systems with a lower degree of commingling (or higher degree of separation). Furthermore, the results also show that two-bin systems can achieve comparable performances **if paper and cardboard are not mixed with light dry recyclables**.

- 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-stream&DRS (DRS for glass bottles *and* DRS for metal cans *and* DRS for plastic bottles, and the joint effect of the three, coexisting with single-stream commingling of paper and cardboard, glass, metal, and plastic) and one-stream (single-stream commingling of paper and cardboard, glass, metal, and plastic), where the net Climate Change impact is about 341-344 kg CO_2-eq per tonne of dry recyclables and the corresponding total recycling rate equals 8%, thus indicating poor recovery of recyclables. By increasing the number of streams, 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 a DRS for 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 -198 kg CO_2-eq per tonne of dry recyclables and total recycling rate of 48%).

The burdens on Climate Change are mainly driven by incineration (contributing 25-36% depending on the cluster; see Annex A), and recycling operations (contributing 12-18% depending on the cluster, see Annex A). The savings are mainly driven by material recovery (contributing 29-44% depending on the cluster; see Annex A) and energy recovered from incineration of residual waste (contributing 10-14% depending on the cluster; see Annex A).



NB: y-axis, expressed as kg CO2-eq per tonne 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. BC: beverage cartons; DRS: deposit refund scheme; GL: glass; MT: metals; PC: paper and cardboard; PL: plastic.

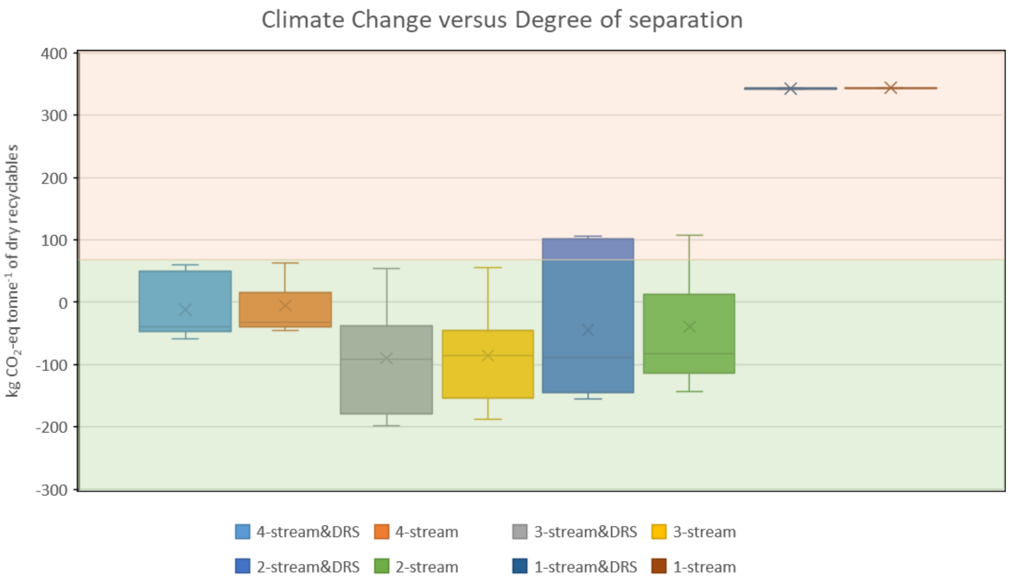
Figure 5: Net impacts on Climate Change

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. separate-streams, dual-stream). 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 a poorer performance and is thus not recommended. The span of each box represents the interquartile range, which represents where 50% of the results lie. 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 each box), and the average net result (cross within each box) (Figure 6).

As described in Section 4.1.2, the scenarios clustered in 4-stream&DRS, 4-stream, 3-stream&DRS, and 3-stream cover the majority (70%) of the different combinations of collection schemes considered herein. The highest (i.e. worst) Climate Change result obtained for these clusters is therefore used as a benchmark (reference line) to identify which collection schemes should be avoided because they lead to a poorer performance (both for the category Climate Change and for recycling rate; red shaded area in Figure 6). Based on this logic, the performances of 1-stream&DRS and 1-stream systems appears to be clearly worse than the remaining systems. On the other hand, different considerations need to be made regarding 2-stream&DRS and 2-stream systems. Indeed, the results show that paper and cardboard need to be kept separate from metal and plastic to deliver performances similar to 4-stream&DRS, 4-stream, 3-stream&DRS and 3-stream systems.

The worst performers correspond to the following specific scenarios, for which the common denominator is the fact that paper and cardboard are not kept separate from the other dry recyclables:

- DRS for glass bottles *and* DRS for metal cans *and* DRS for plastic bottles, and the joint effect of the three, coexisting with commingling of paper and cardboard, plastic, metal, and beverage cartons (i.e. dual-stream collection coexisting with a DRS falling in the red area in Figure 6); commingling of paper and cardboard, plastic, metal, and beverage cartons (i.e. dual-stream collection falling in the red area in Figure 6).
- DRS for glass bottles *and* DRS for metal cans *and* DRS for plastic bottles, and the joint effect of the three, coexisting with commingling of paper and cardboard, glass, metal, and plastic (i.e. single-stream collection coexisting with a DRS).
- Commingling of paper and cardboard, glass, metal and plastic (i.e. single-stream collection).



NB: (y-axis, expressed as kg CO2-eq per tonne of dry recyclables). The area of the graph is divided into 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). The cut-off between beneficial and non-beneficial is based on the worst Climate Change result obtained for 4-stream&DRS, 4-stream, 3-stream&DRS, and 3-stream systems which represent 70% of the different combinations of collection schemes considered herein.

Figure 6: Box-and-whisker plot of the distribution of the net results obtained for Climate Change

4.3.1.2 Other environmental impact categories: summary

Annex A reports the complete list of results obtained for the remaining impact categories which, 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 the incinerator or energy consumption at sorting and recycling plants, depending on the EU grid mix) and not so much by material recovery efficiencies.

4.3.2 Environmental life cycle costs

The total environmental costs represent the net cost of the waste management systems considered herein, including expenses for any operation involved, revenues generated, and environmental taxes. The environmental 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 or incineration/landfilling);
- costs of recycling and material recovery (including the costs related to recycling 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).

For the sake of simplicity, we will henceforth refer to ‘costs’ instead of ‘environmental costs’.

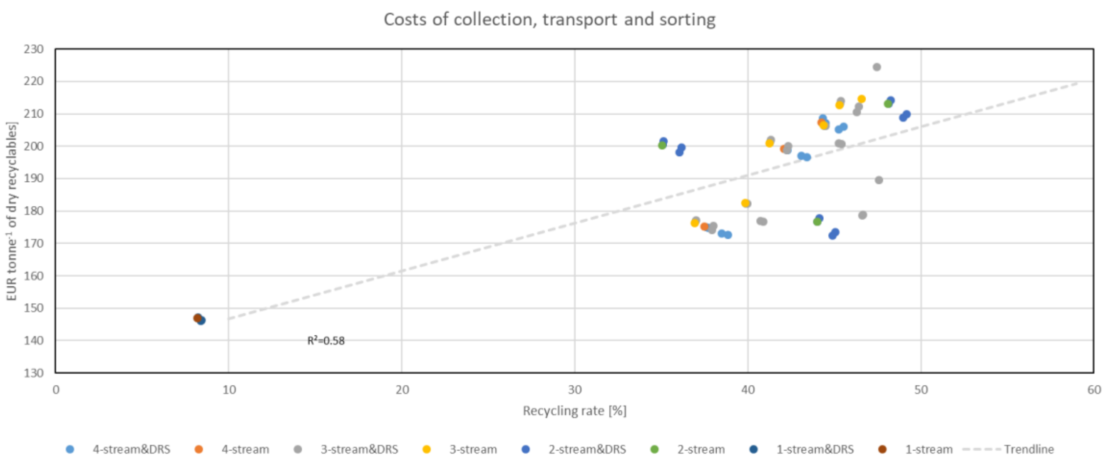
4.3.2.1 Costs of collection, transport and sorting

The collection, transport and sorting costs are displayed in **Error! Reference source not found.**, which s hows the relationship between collection, transport and sorting costs and the total recycling rate for dry recyclables (ranging from 8% to 49%). A linear regression was performed on the data (shown by the trendline in **Error! Reference source not found.**), and its goodness-of-fit is calculated at 0.58, meaning that a pproximately 58% of the 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 the following:

- Systems with a degree of separation of three or four streams generally have higher collection, transport and sorting costs.
- 2-stream&DRS and dual -stream systems characterised by commingling of glass, metal and plastic and separate collection of paper and cardboard (or paper and cardboard together with beverage cartons) have the highest costs while achieving the highest recycling rates. This is however based on a single set of primary data.
- The increase in collection, transport and sorting costs from a lower to higher degree of separation is broadly proportional. The increase is around EUR 0-78 per tonne of dry recyclables, corresponding to about EUR 0-14 per capita per year.

The clusters with the lowest collection, transport and sorting costs are the 1-stream&DRS (DRS for glass bottles *and* DRS for metal cans *and* DRS for plastic bottles, and the joint effect of the three, coexisting with commingling of paper and cardboard, glass, metal, and plastic) and single-stream (commingling of paper and cardboard, glass, metal, and plastic), where collection, transport and sorting costs are about EUR 146-147 per tonne of dry recyclables. By increasing the number of streams collected, Figure 7 shows that both the total recycling rate and the total collection, transport and sorting costs increase. Specifically, the clustering of scenarios with the highest costs appears to be the 3-stream&DRS and, more specifically, the scenario with a DRS for glass bottles coexisting with commingling of glass and metal, plastic and beverage cartons, and paper and cardboard collected as a separate-stream (EUR 224 per tonne of dry recyclables).



NB: (y-axis, expressed as EUR per tonne 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.

Figure 7. (Environmental) costs of collection, transport and sorting

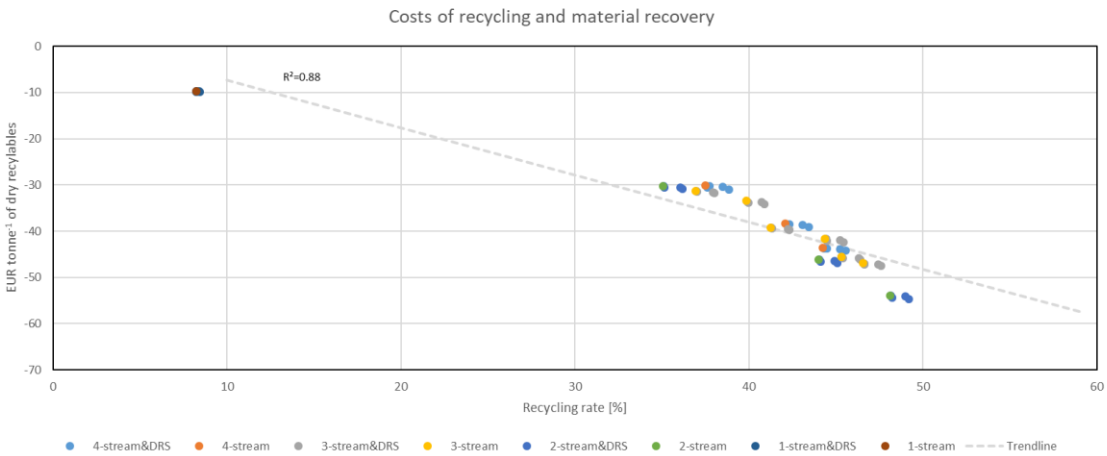
4.3.2.2 *Costs of recycling and material recovery*

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 8% to 49%). A linear regression was performed on the data (shown by the trendline in Figure 8), and its goodness-of-fit is calculated at 0.88, indicating a good fit of the linear regression with the data points.

The trend observed in the results suggests the following:

- Systems with a degree of separation of two, three or four streams have higher overall net incomes 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. single-stream system).
- There is no clear evidence that four-stream systems achieve higher revenues than three- or dual-stream systems. This shows 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 the recycling and material recovery stage.

The clusters with the highest costs (lower net income) are the 1-stream (commingling of paper and cardboard, glass, metal, and plastic) and 1-stream&DRS (DRS for glass bottles *and* DRS for metal cans *and* DRS for plastic bottles, and the joint effect of the three, coexisting with commingling of paper and cardboard, glass, metal, and plastic), resulting in a total cost of EUR -10 per tonne of dry recyclables (or net income of EUR 10 per tonne of dry recyclables). The cluster of scenarios with the highest income was the 2-stream&DRS (and, specifically, the scenario with a DRS for glass bottles *and* a DRS for metal cans *and* a DRS for plastic bottles, and the joint effect of the three, coexisting with glass, metal and plastic, and paper and cardboard collected as separate-streams) with a net income around EUR 54-55 per tonne of dry recyclables.



NB: (y-axis, expressed as EUR per tonne 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.

Figure 8. (Environmental) costs of recycling and material recovery

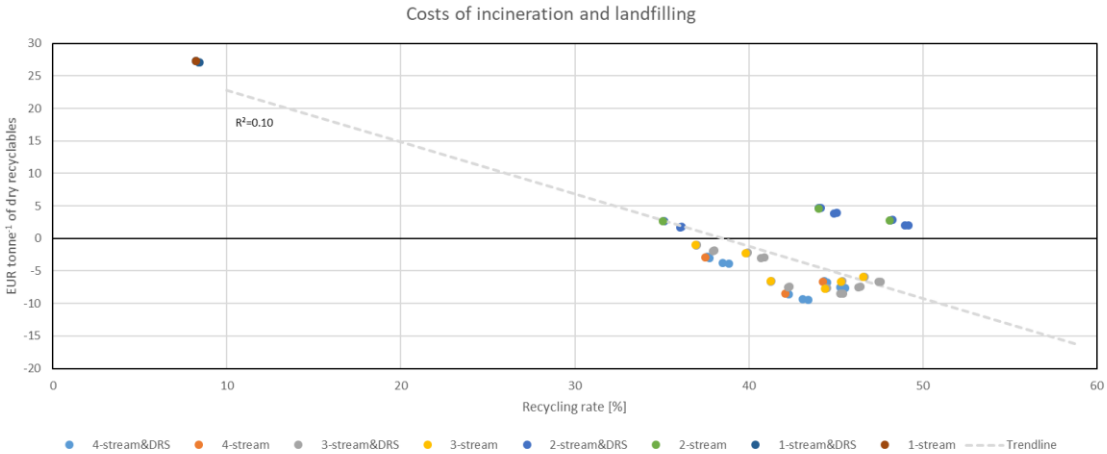
4.3.2.3 *Costs of incineration and landfilling*

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 8% to 49%). A linear regression was performed on the data (shown by the trendline in Figure 9), and its goodness-of-fit is calculated at 0.10, indicating a poor fit of the linear regression with the data points.

The trend observed in the results suggests that the higher the number of streams collected, 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, negative costs (i.e. a net income for this stage of the management system) are still observed, because residual waste is converted into energy, providing revenues which exceed 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 for glass bottles *and* DRS for metal cans *and* DRS for 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 EUR 27 per tonne of dry recyclables. On the other hand, the cluster of scenarios performing the best are 4-stream&DRS, 4-stream, 3-stream&DRS, and 3-stream (ranging from EUR -9 to EUR -1 per tonne of dry recyclables) and, more specifically, the scenarios with the lowest costs per tonne are the ones where a DRS on glass bottles *and* a DRS on metal cans *and* a DRS on plastic bottles, and the joint effect of the three, coexist with a separate-stream collection of paper and cardboard, glass, metal, and plastic, while beverage cartons are collected together with the residual waste (i.e. 4-stream&DRS and 4-stream), and the scenario where a DRS on glass bottles coexists with commingling of glass and metal, and separate-stream collection of plastic and of paper and cardboard, while beverage cartons are collected together with the residual waste (i.e. 3-stream&DRS).

Notice that the 2-stream&DRS and 2-stream scenarios that are achieving the highest recycling rates (i.e. commingling of glass, metal and plastic, and collection of paper and cardboard/paper and cardboard and beverage cartons) incur net costs. Indeed, in these scenarios the amount of waste going to residual waste is the lowest and, hence, less energy can be recovered, lowering revenues. However, at a system-wide level this is compensated by higher revenues from material recovery.



NB: (y-axis, expressed as EUR per tonne of dry recyclables) versus total recycling rate (x-axis, expressed as %). Note that revenues from energy recovery are also included. The linear trendline calculated based on the results is shown together with the related R^2 value.

Figure 9. (Environmental) costs of incineration and landfill

4.3.2.4 Total costs

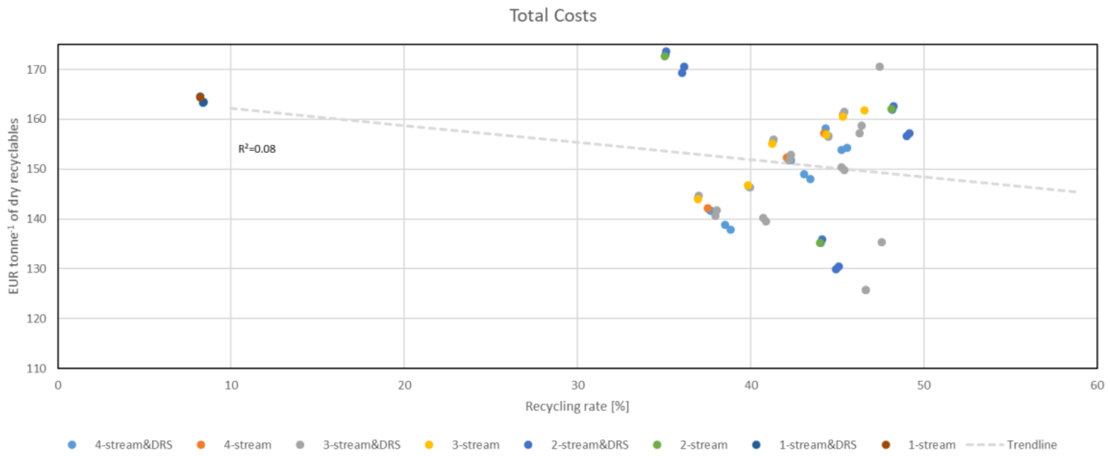
Figure 10 shows the relationship between net total costs and the total recycling rate for dry recyclables (ranging from 8% to 49%). A linear regression was performed on the data (shown by the trendline), and its goodness-of-fit is calculated as 0.08, meaning that approximately 10% of the variability observed in the target variable (i.e. the net total environmental costs) is explained by the regression model.

The trend observed in the results suggests the following:

- Systems with a degree of separation of three streams (three-bin) or four streams (four-bin) have overall significantly lower total costs than systems with a lower degree of separation (or higher degree of commingling; i.e. one- or two-bin systems).
- There is no clear evidence that four-bin systems have overall lower total costs than three-bin systems. This shows that a certain degree of commingling is, 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 total costs range from EUR 126 to EUR 174 per tonne of dry recyclables. The clusters performing the worst are the 2-stream&DRS (DRS for glass bottles *and* DRS for metal cans *and* DRS for plastic bottles, and the joint effect of the three, coexisting with commingling of paper and cardboard, plastic, metal and beverage cartons, and separate-stream collection of glass) and 2-stream (commingling of paper and cardboard, plastic, metal, and beverage cartons, and separate-stream collection of glass) where the total cost was around EUR 171-174 per tonne of dry recyclables. These scenarios incur high collection costs due to the high cost of collecting lightweight recyclables (assumed to be EUR 288 per t^{-1}) and poor performance in collection rate resulting in low revenues from recycling overall. Other dual- and three-stream systems are subject to the same collection costs, but have higher collection rates, and thus recycling rates, hence resulting in lower total costs.

By increasing the number of separated streams the total costs decrease while the recycling rate increases, due to the higher recovery of recyclables and revenues thereby obtained. However, the results also show that the revenues obtained by recycling the dry recyclables do not fully compensate for the above-mentioned costs, suggesting that market prices of most secondary materials are still too low.



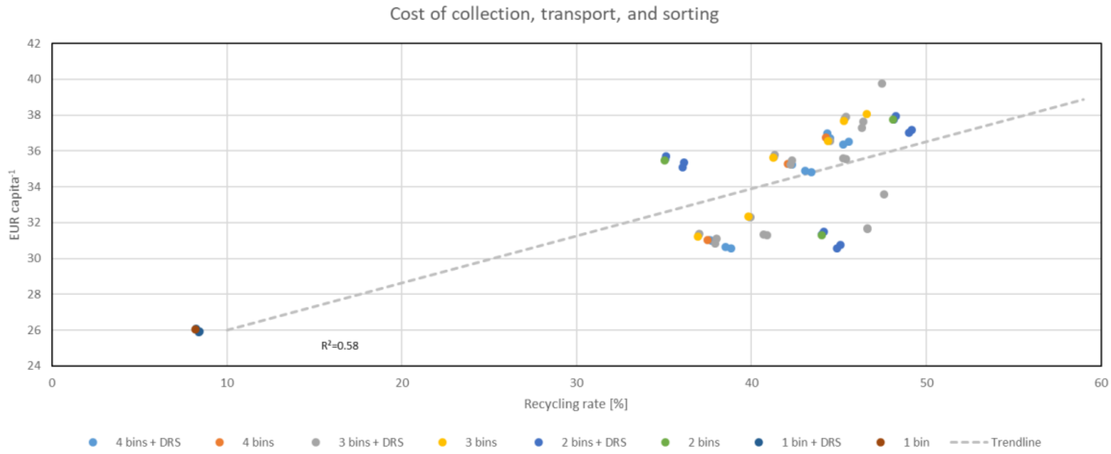
NB: The linear trendline calculated based on the results is shown together with the related R^2 value.

Figure 10. Total (environmental) costs (y-axis, expressed as EUR per tonne of dry recyclables) versus total recycling rate (x-axis, expressed as %).

The total costs are mainly driven by collection, transport and sorting costs (contributing 77-86% depending on the cluster), followed by recycling and material recovery costs (contributing 5-21% depending on the cluster), and, finally, incineration and landfill costs (contributing 0.5-15% depending on the cluster).

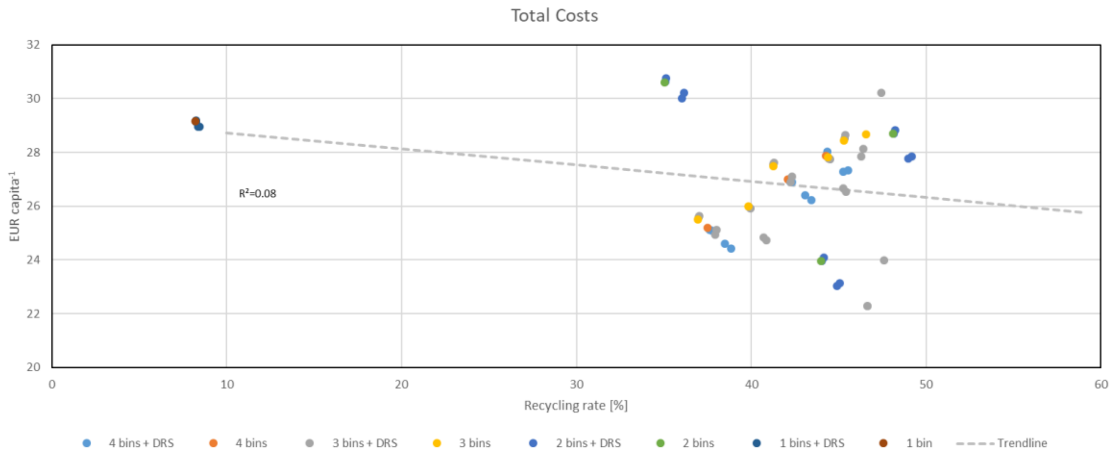
As seen in Figure 10, the low R^2 for the total costs suggests that there is ultimately little correlation between total costs and recycling rate.

Expressed as *costs per capita* (from a citizen's perspective), costs for collection, transport and sorting (cf. above) range from EUR 26-40 per $capita^{-1}$ and Total costs in the EUR 22-31 per $capita^{-1}$ range, as illustrated in the two figures below (cf. Figure 7 and Figure 10, respectively).



NB: The linear trendline calculated based on the results is shown together with the related R² value.

Figure 11. Total (environmental) cost of collection, transport and sorting (y-axis, expressed as EUR per capita^{-1}) versus total recycling rate (x-axis, expressed as %).



NB: The linear trendline calculated based on the results is shown together with the related R² value.

Figure 12. Total (environmental) costs (y-axis, expressed as EUR per capita^{-1}) and total recycling rate (x-axis, expressed as %).

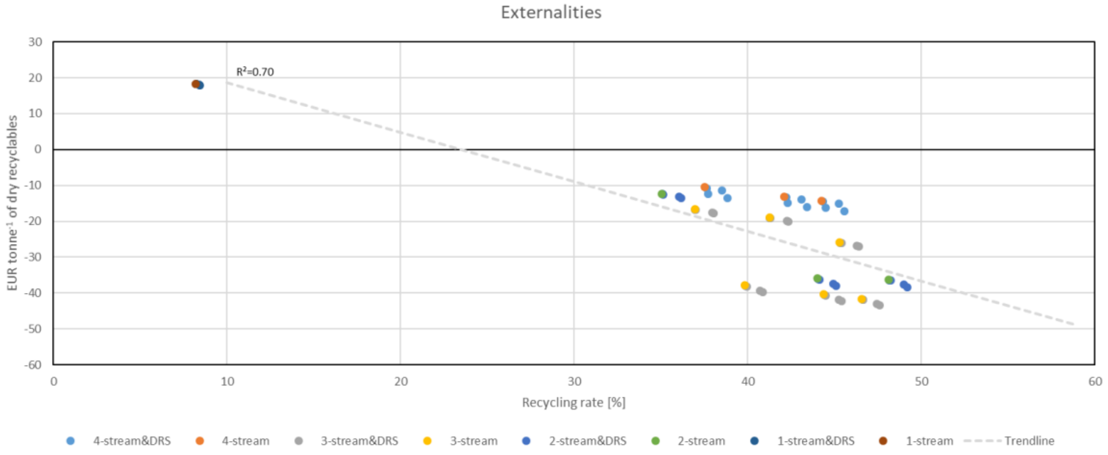
4.3.3 Full environmental life cycle costs

4.3.3.1 Environmental externalities

The results obtained are displayed in Figure 13, where the external 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 its goodness-of-fit is calculated at 0.70, meaning that approximately 70% of the variability observed in the target variable (i.e. the externalities) is explained by the regression model.

The trend observed in the results shows that in general the higher the number of streams, 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 EUR -43 per tonne of dry recyclables (specifically, in the cluster 3-stream&DRS, specifically for the scenario where glass bottles only and 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 EUR 18 per tonne of dry recyclables (specifically, for the clusters 1stream&DRS and 1-

stream).



NB: The linear trendline calculated based on the results is shown together with the related R^2 value.

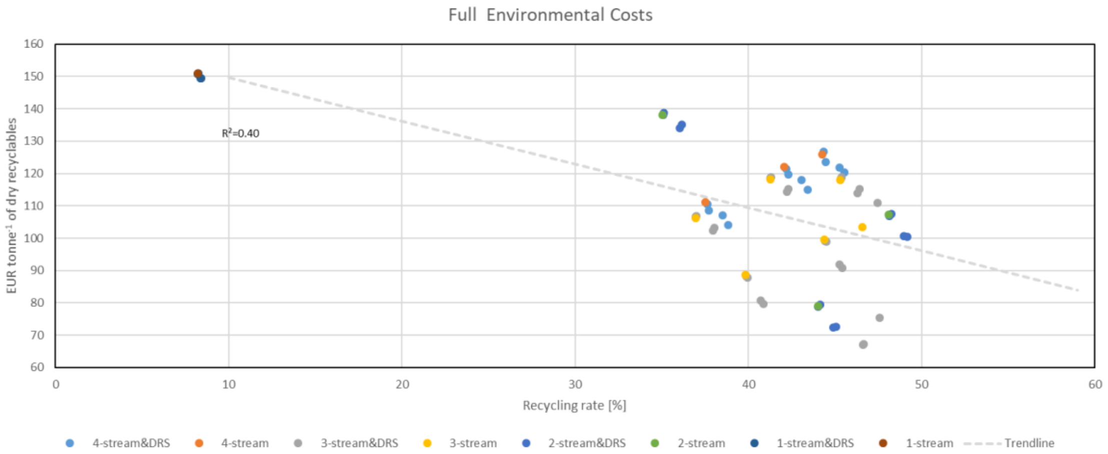
Figure 13. External costs (y-axis, expressed as EUR per tonne of dry recyclables) versus total recycling rate (x-axis, expressed as %).

4.3.3.2 Full Environmental Costs

By summing the Total Environmental Costs (excluding from these costs the already internalised environmental taxes, such as landfill and incineration taxes) and the External costs, the Full Environmental Costs are obtained.

Figure 14 shows the relationship between Full Environmental Costs and the total recycling rate for dry recyclables (ranging from 8% 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 0.40, indicating a fair fit.

The trend observed in the results suggests that the higher the number of streams, the higher the recycling rate, and the lower the Full Environmental Costs. The clusters performing the worst are the 1-stream&DRS (DRS for glass bottles *and* DRS for metal cans *and* DRS for 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 Full Environmental Costs are EUR 149-151 per tonne of dry recyclables. By increasing the number of streams collected, it is clear from Figure 14 that the Full Environmental Costs decrease and the total recycling rate increases, due to the higher recovery of recyclables.



NB: The linear trendline calculated based on the results is shown together with the related R^2 value.

Figure 14. Full Environmental Costs (y-axis, expressed as EUR per tonne of dry recyclables) versus total recycling rate (x-axis, expressed as %).

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 lie. 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 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, and by 2-stream and 2-stream&DRS (especially for the systems commingling glass, metal and plastic, and collecting paper and cardboard or paper and cardboard with beverage cartons). On the other hand, the scenarios with the lowest employment are 1-stream&DRS and 1-stream as these scenarios are characterised by high levels of commingling, low collection rates, and low recycling rates.

In the case of dual-stream, the systems yielding higher employment correspond to the ones where glass, metal and plastic are commingled, while paper and cardboard is collected as a separate-stream or together with beverage cartons. These scenarios are characterised by the highest collection rates, thus suggesting that the higher the amount of waste recycled (and, therefore, collected), the higher the number of jobs created. These considerations hold true regardless of the commingling system and number or streams.

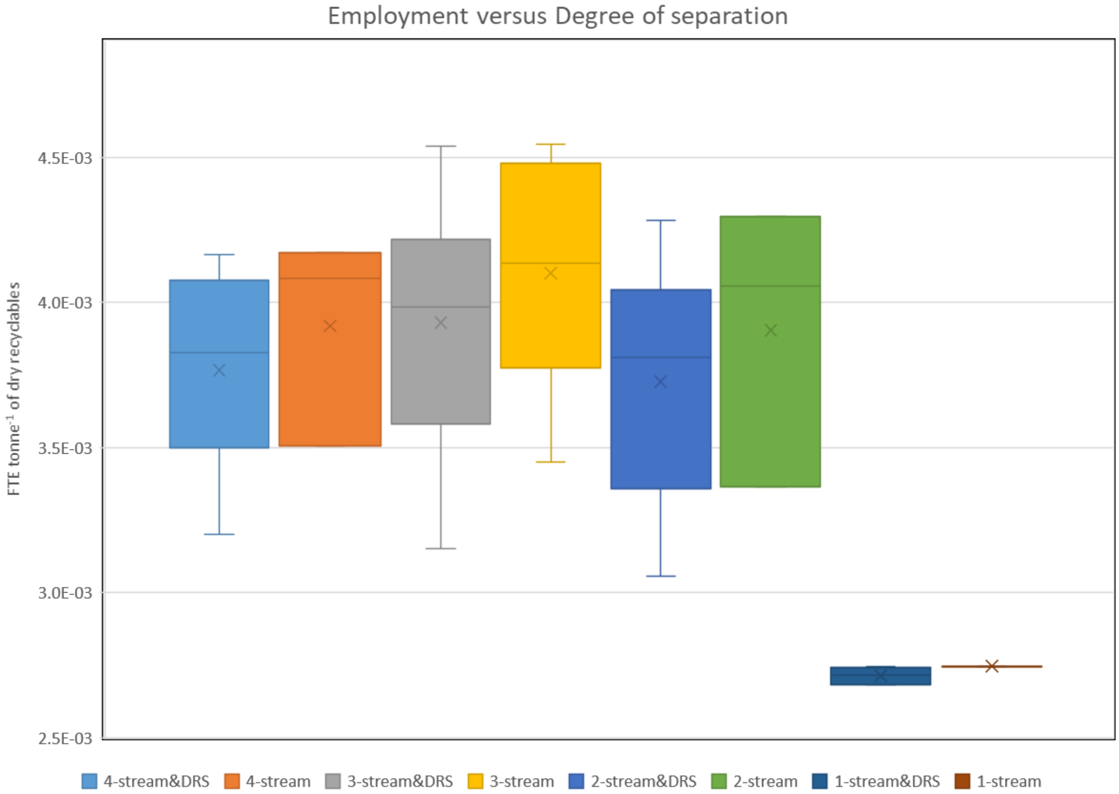
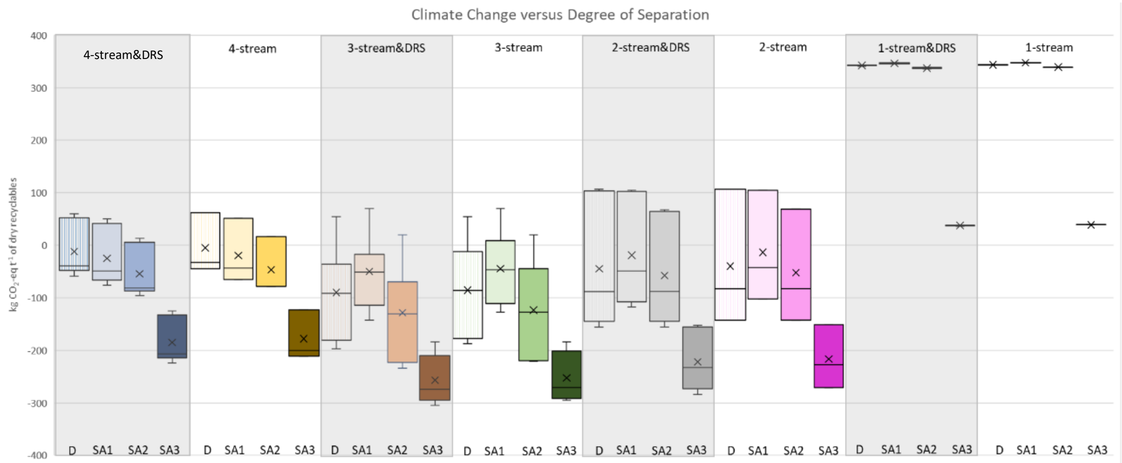


Figure 15. Box-and-whisker plot representing the total employment (y-axis, expressed as FTE per tonne of dry recyclables) against the different degrees of separation

4.3.5 Sensitivity analyses

The results obtained for Climate Change for the sensitivity analysis performed on the efficiencies of the sorting plant (i.e. "SA1" in Figure 16), on the collection rate of plastic (i.e. "SA2" in Figure 16), and on the addition of an advanced centralised sorting of residual waste (i.e. "SA3" 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.



NB:(y-axis, expressed as kg CO2-eq per t-1 of dry recyclables) against the different degrees of separation for the default scenarios ("D"), the sensitivity analysis performed on the sorting efficiencies ("SA1"), on the collection rates of plastic ("SA2"), and the sensitivity analysis performed on the advanced centralised sorting of residual waste ("SA3").

Figure 16. Box-and-whisker plot representing the Climate Change impacts

Figure 16 shows that, overall, the same trend in the results as for D is observed for SA1, SA2 and SA3. Indeed, 4-stream and 4-stream&DRS, 3-stream and 3-stream&DRS, and 2-stream and 2-stream&DRS (especially when glass, metal, and plastic are commingled, and paper and cardboard are collected as a separate stream or together with beverage cartons) scenarios perform as the ones contributing the highest net savings, while the ones performing the worst are again 1-stream&DRS and 1-stream scenarios.

When comparing the results of D with SA1 (where we change the efficiency of the sorting plant for commingled material based on the primary data from a plant situated in Italy), two conclusions can be inferred: i) the overall ranking of scenarios remains the same, thus confirming the robustness of the default assumptions; ii) lower savings on Climate Change are observed for the case of three-, dual- and single-stream systems and their variants with DRS. This is explained by the lower recovery rate assumed in SA1 for aluminium sorting than that previously assumed in D (around 57% in SA1 versus around 90% in D; for details please refer to Annex A). Despite aluminium representing only 4% of the total dry recyclables, the influence of its recovery rate on Climate Change is significantly larger than other recyclables, such as plastic. From a total material recovery perspective, however, the recycling rate increases relative to D as more plastic is recycled (where plastic represents 24% of the total dry recyclables) as the plastic recovery rate at sorting is higher in SA1 than in D (for details please refer to Annex A). Notice that four-stream systems are not affected by changes in sorting plant efficiencies (as for three-, dual- or single-stream) because metals are collected as a separate-stream and partly via a DRS.

When comparing the results of D with SA2, 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. The recycling rates calculated for SA2 span from 11% (1-stream and 1-stream&DRS scenarios) to 51%, corresponding to the scenarios where a DRS is enforced for glass bottles only and for glass bottles, metal cans and plastic bottles, glass and metal are commingled, and plastic is commingled with beverage cartons (3-stream&DRS)

When comparing the results of D with SA3, 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 the recovery of additional material that would have otherwise been lost, especially metals and plastic, whose recycling incurs important GHG benefits. Yet, this should not be seen as a competing scheme to separate collection at source but, on the contrary, as an additional and complementary management stage. This can be derived by the fact that single-stream systems complemented with centralised sorting of residual waste never achieve better performances on Climate Change than dual-, three- or four-stream systems complemented with centralised sorting of residual waste. The same result is in general valid for the other impact categories. In a nutshell, centralised sorting of residual waste increases total material recovery and the related environmental savings, but it is not a substitute for separate collection at source.

4.4 Limitations of the study

The following limitations of this study have been identified:

- The data for separate-stream collection differs across the different dry recyclables considered. For separate-stream collection of paper and cardboard, the number of references considered for the share of impurities was 15, while for the collection rate it was 25. For separate-stream collection of glass, the number of references considered for the share of impurities was 6, while it was 31 for the collection rate. For separate-stream collection of metals, the number of references considered for the share of impurities was 1, while it was 11 for the collection rate. Finally, for separate-stream collection of plastic, the number of references considered for the share of impurities was 3, while it was 8 for the collection rate (Annex A).

- The data for commingled single-stream collection was 1 data point for share of impurities based on expert judgement, while for collection rates 4 references were considered (Annex A).

- The data considered in the other commingling systems (i.e. dual-stream, three-stream, and four-stream) varies from 1 to 11 data points retrieved from literature considered for shares of impurities, and from 1 to 4 for collection rates depending on the system considered (Annex A). Note that the case of the system where glass, metal and plastic are commingled together while paper and cardboard are collected separately together with beverage cartons (i.e. one of the dual-stream systems considered in the assessment) is based on primary data from a specific area, situated in Italy (i.e. only one set of data).

- 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 the labour cost in the total cost as reported in Utilitalia & Bain (2018). Furthermore, the cost of commingled waste collection was assumed to be the same for all commingling setups assessed, except for the configuration where glass, metal and plastic are commingled (i.e. one of the dual-stream systems considered in the assessment). As for the other waste streams, the employment of commingled collection was based on the share of the labour cost in the total cost as reported in Utilitalia & Bain (2018).

- It is important to note that herein all cost functions are assumed to be linear. While this is true for treatment facilities (especially for recycling under specific capacities), this is not applicable to collection costs as unit costs vary not only with type of collection (e.g. door-to-door, bring collection points), but also with the collection yield (e.g. the marginal cost of collection *increases* when the collection rates are higher, either because it is more costly to collect the last units of waste, or because the amount of impurities increases)[15]. These considerations on collection costs have not been taken into account in the current assessment, but may be considered in future developments of the model used.

- Interviews with operators consistently highlighted that the implementation of a DRS would significantly affect them, considering that a substantial part of valuable material (e.g. PET bottles, metal cans), which are today associated with significant revenues, would be lost to the advantage of deposit refund scheme operators. The implementation of a 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 a DRS). Therefore, by enforcing a 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 taken at home to segregate waste, as well as the space occupied by multiple bins to separate different fractions, 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 four-, three-, dual- or single-stream collection (that might – or might not – correspond to having four, three, two or one additional bin) has not been accounted for as this was outside the scope of the analysis. We

[15] Bohm, R. A., Folz, D. H., Kinnaman, T. C., Podolsky, M. J. (2010). The cost of municipal waste and recycling programs. Resources, Conservation and Recycling, 54, pp. 864-871. https://doi.org/10.1016/j.resconrec.2010.01.005

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 was unidirectional: in the overwhelming majority of contexts, separation had been lagging behind objectives and represented a key limiting factor in increasing, for example, the quantity and quality of recycling. Most municipalities – and most countries at an aggregated level – are still 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 one to two waste flows, these start reducing with a high number of fractions (above three). When factoring 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 out above, the present study did not take into account the 'shadow' or hidden costs of separation at the household level, which may become significant as the number of separate fractions increases. These would arise from:

a) the 'shadow' time taken 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 costs for citizens (cf. point (a) above) 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[16], where some plastics (e.g. not under a 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).

However, it is important to stress that only a few places where waste separation is already very advanced can even consider this type of trade-off: 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 forthcoming recycling targets for example. Notably, this regards the separate collection at the source of bio-waste and paper and cardboard.

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

5 Conclusions and recommendations for dry recyclables collection

5.1 Main conclusion

The evidence obtained via life cycle assessment and costing performed on 65 management scenarios, reflecting the possible variations of commingling systems for dry recyclables across the EU, indicates the following:

- Systems with a degree of separation of three streams or four streams in general perform significantly better than systems with a lower degree of separation (or higher degree of commingling, i.e. single- or dual-stream systems) from a climate change perspective. Results obtained for a specific configuration of dual-stream system, namely commingling of glass, metal and plastic while collecting paper and cardboard as a separate-stream or commingled with beverage cartons, show similar performances to three- and four-stream systems.
- There is no clear evidence that four-stream systems perform better than three-stream systems, either environmentally or economically. This reveals that a certain degree of commingling (for example, three-stream or a dual-stream systems where glass is commingled with metal and plastic while paper and cardboard are collected as a separate-stream or commingled with beverage cartons) is acceptable and, based on the evidence available to date, does not lead to detrimental environmental and economic effects compared with systems with a higher degree of separation.
- Single-stream collection of dry recyclables achieves the worst environmental performance across all the impact categories considered in the assessment, followed by dual-stream systems, except for dual-stream systems where glass, metal and plastic are commingled and paper and cardboard are collected as a separate-stream or commingled with beverage cartons (in the latter configuration, the performances achieved in terms of recycling rates and environmental impacts are comparable with three- and four-stream systems). This holds true even when all these configurations are accompanied by a deposit refund scheme (DRS) on selected material fractions such as glass bottles, metal cans and PET bottles.
- Single-stream collection of dry recyclables achieves the worst economic performance (environmental costs, i.e. financial costs plus environmental taxes) and the worst *full* environmental cost performance (i.e. financial costs plus external costs, e.g. monetised environmental emissions). 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 a deposit refund scheme (DRS) on selected material fractions such as glass bottles, metal cans and PET bottles.
- Systems with three and four streams incur higher collection, sorting and transport costs but less overall costs at a system-wide level relative to single-stream systems, thanks to the revenues from secondary materials. The same applies to the full environmental costs. However, when compared against dual-stream systems, the ranking is not as neat because dual-stream systems have competitive costs and the external costs gap is not as significant as for single-stream systems.
- Generally, the higher the recycling rate, the lower the net Climate Change impact of the waste management system.

5.2 Noncompliant practices

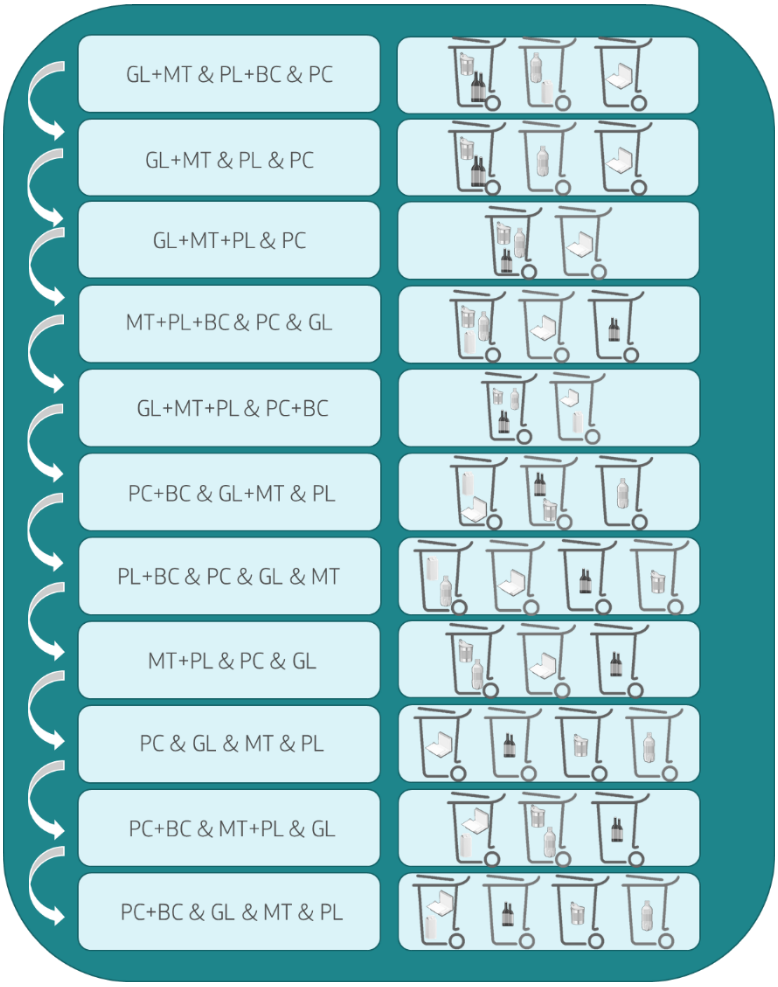
Based on the evidence built via collection of data and subsequent modelling in this study, it appears that, overall, single-stream commingling systems achieve a significantly worse environmental and economic performance compared with systems with a higher degree of separation, notably three- or four-stream systems. A similar conclusion applies to dual-stream systems where paper and cardboard, plastic, metal and beverage cartons are commingled, with respect to the environmental dimension, although the environmental performance gap relative to three- or four-stream systems is not as pronounced as for single-stream systems. Results obtained for a specific configuration of dual-stream system, namely commingling of glass, metal and plastic while collecting paper and cardboard as a separate-stream or commingled with beverage cartons, show however similar performances to three- and four-stream systems.

Based on our analysis and considering paragraph 2, Article 10 of the Waste Framework Directive, as amended by Directive (EU) 2018/851, it therefore appears that commingling of all dry recyclables in a single stream clearly leads to detrimental environmental effects while increasing 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 where paper and cardboard, plastic, metal and beverage cartons are commingled, as they show systematically poorer environmental performances than three- or four-stream systems. However, the environmental gap with three- or four-stream systems is not as pronounced as that of single-stream systems and their lower conventional costs somehow mitigate their full environmental impact (which is the sum of environmental costs and monetised environmental emissions). Dual-stream systems where glass, metal and plastic are commingled, while paper and cardboard are collected as a separate-stream or commingled with beverage cartons, achieve instead comparable environmental and economic performances to three- and four-stream systems.

5.3 Best practices

Within this study we define best practices as those systems with the best performance on Climate Change, as this shows a great correlation with the recycling rate. Both climate change mitigation and increased recycling rate (as a proxy for increased material circularity) are main objectives of the EU Green Deal and Circular Economy Action Plan. From this perspective, the best commingling scenarios are three-stream and dual-stream systems, as illustrated in Figure 17. For all these scenarios, our results indicated that including a DRS (glass bottles, metal cans and PET bottles) further improves the performance.



NB: Notice that the performance on Climate Change is very well correlated to the recycling rate indicator. The following acronyms are used: "BC" waste beverage cartons; "GL" glass waste; "PC" paper and cardboard waste; "PL" plastic waste; "MT" metal waste.

Figure 17. Illustration of the best commingling practices for dry recyclables based on their performance on Climate Change.

The literature review conducted over the course of this project (Albizzati, Antonopoulos, et al. (2023b) and consultations with waste collection operators indicated that commingling of glass with plastic waste may, in general, be not ideal because of the contamination of plastic waste with glass fines and dust. However, the results of the life cycle assessment and costing based on actual primary data from operators of the North-East of Italy applying this scheme show that this commingling scheme performs comparably to the best performing schemes. While these results are based on only one set of primary data, this us tells that i) *a priori* conclusions on the performance of glass, plastic and metals commingling cannot be inferred, and ii) sorting plants can be configured to handle various types of commingled inputs effectively, including glass with plastic and metals.

The inclusion of centralised sorting 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 all systems, thanks to the additional recovery of materials. However, our findings also indicate that such centralised sorting plants for residual waste should not be considered, in general, as an *alternative* to separate collection at source, but rather as a *complement* or add-on. Note that this study did not investigate the opportunities for separating and recovering selected material fractions, e.g. selected plastic packaging fractions, directly via centralised sorting plants while avoiding separately collecting them at source, as practiced in Norway (and the environmental, economic and social impacts thereof). These should be seen as further variations of the commingling systems assessed in this study, targeting selected fractions (e.g. a share of the total plastic packaging waste), and were out of the scope of this study. We suggest that *ad hoc* follow-up studies using primary data be performed to specifically assess the environmental and socioeconomic performance of these variants.

Our analysis also illustrates 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 proportion of uncollected plastic waste currently ends up being incinerated. A diversion of plastic waste to recycling incurs two simultaneous and cumulative benefits relative to the *status quo*: i) it avoids GHG emissions at incinerators (where it would otherwise partly end up) *and* ii) it avoids GHG emissions associated with primary plastic production (which would otherwise have to be produced, *ceteris paribus*).

Finally, in the context of waste collection it is important to remark that one solution does not fit all, i.e. collection depends on several factors (e.g. geography, demography, climate) and what is successful in one specific context might not be in another. In this sense, this study does not and cannot cover all the possible combinations that may be found in the EU-27's different regions. However, by covering 65 management scenarios complemented with three additional sensitivity analyses, it clearly identifies the worst and best commingling schemes under generic conditions that are widely applicable to the EU-27 context.

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List of abbreviations and definitions

See also Section 2.1

BC	Beverage Carton (Waste)
BOF	Basic Oxygen Furnace
CAPEX	Capital Expenditure
CLCC	Conventional Life Cycle Costing
DRS	Deposit Refund Scheme (or System)
EAF	Electric Arc Furnace
EC	European Commission
ECS	Eddy Current System
EEA	European Environment Agency
EU	European Union
EWR	Early Warning Report
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
MRF	Material Recovery Facility (sorting plant)
MSW	Municipal Solid Waste (= 'Municipal Waste' as per WFD definition)
MT	Metal Waste
NIR	Near-Infrared (sensor / spectroscopy)
OCC	Old Corrugated Cardboard
OPEX	Operating Expenditure
PC	Plastic and Cardboard waste
PE	Polyethylene
PET	Polyethylene Terephthalate
PL	Plastic Waste
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinylchloride
RDF	Refuse-derived fuel
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

The spreadsheet file is available for download on the JRC repository website where this report is located.

Worksheet title	Title	Caption
A1	Waste composition	Waste composition of paper and cardboard, beverage carton, plastic, metal, and glass. Amounts are presented as percentages and rounded.
A2	Data regarding collection rate and share of targeted material	Summary table of data used in the assessment. After the summary table, all the data used to calculate the 75th percentile are reported for each dry recyclable.
A3	Sorting facilities	Efficiencies of sorting facilities assumed in the default case and in the sensitivity analysis where transfer coefficients are modified based on primary data obtained from an Italian sorting facility (SA1).
A4	Composition of impurities	Composition of the impurities of the collected streams, either as an individual separate stream (e.g. only glass) or different combinations of commingling. The impurities of column B, for example, represent the material fractions that are collected together with paper and cardboard when collected as a separate stream. The composition is based on Edjabou et al. (2021)*. Values are expressed as percentages and are rounded.
A5	Cost data of collection	Summary table of data used in the assessment. After the summary table, all the data used to calculate the 75th percentile are reported for each dry recyclable. Values are all reported in EUR_{2020}.
A6	Contribution analysis of climate change in the default case	The contribution analysis for climate change in the default scenario is herein presented for the different degrees of separation considered in the study. For each cluster (e.g. 4-stream&DRS), the average contribution of the processes is shown for the sake of clarity. A total of 65 combinations are included overall. The y-axis is expressed as percentages.
A7	Results obtained for the remaining impact categories in the default case	The results for the impact categories other than climate change are herein presented as box-and-whisker plots.
A8	Hierarchy of results for climate change and full environmental costs	The results obtained for the default case are herein shown for Climate Change, Externalities, and Full Environmental Costs.

		The results of Externalities and Full Environmental Costs have been ordered from the best to the worst performing scenarios identified for Climate Change.

*Edjabou, M. E., Takou, V., Boldrin, A.,Petersen, C., and Astrup, T. F. (2021). The influence of recycling schemes on the composition and generation of municipal solid waste. Journal of Cleaner Production (295), 126439. https://doi.org/10.1016/j.jclepro.2021.126439

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