COLLECTORS

Work package 3

Quantification of costs and benefits

Report of LCA meta-analysis and guidance document for LCA of waste collection systems

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Credits

Disclaimer

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Summary

Well-performing waste collection systems (WCS) are a key element for closing material loops and moving towards a circular economy. WCS comprise the collection and sorting of waste and thus determine the quantity and quality of waste collected. This in turn influences activities such as treatment, recycling and final disposal, and ultimately the amount of secondary materials available to substitute primary production inputs.

This report provides a methodology and thus guidance for performing life cycle assessment (LCA) studies for waste collection systems. The methodology adopts a broad systemic perspective in order to capture not only the potential environmental impacts generated by the WCS themselves, but also the consequences of quality and quantity of collected wastes for resource recovery and substitution of primary production inputs. The life cycle stages covered include the entire life cycle of the materials: primary production with possible substitution of primary through secondary materials, waste collection and sorting, as well as recycling and disposal. The use phase of products before they become waste is excluded, as it can be assumed not to change as a result of decisions at the WCS. The substitution potential of secondary materials is determined based on the assumption of a steady-state system and the limits to the recyclability of secondary materials are considered (e.g. paper cannot be recycled indefinitely, but instead always requires a certain amount of virgin fibres). If materials cannot be recycled in a closed loop (i.e. within their original application due to an oversupply), open-loop recycling is assumed.

The methodology is generic and can be applied to any European WCS to assess, for example, the environmental consequences of choices made at the collection stage. However, the data can and should be adapted for each specific WCS studied, e.g. by stakeholder consultation (interviews or questionnaires) and published data (i.e. in scientific literature or national and regional reports).

We have tested the methodology in this report using at the example of paper and packaging waste (PPW), although it could also be applied to other WCS, such as waste electrical and electronic equipment (WEEE) and construction and demolition waste (CDW). It is applied to 5 PPW cases, 5 WEEE cases and 2 CDW cases as part of Task 3.3 of the COLLECTORS project (deliverable 3.3: Report of recommendations for improvement of single systems and optimum operation conditions of

waste collection systems). The methodology is consistent to ensure a fair basis for comparison between different WCS.

Contents

List of abbreviations

CDW	construction and demolition waste
EU	European Union
GWP	global warming potential
LCA	life cycle assessment
PPW	paper and packaging waste
WCS	waste collection systems
WEEE	waste electrical and electronic equipment

1 Introduction

1.1 The COLLECTORS project

The EU's vision of sustainable economic growth and global competitiveness will be facilitated by the transition towards a circular economy, with its aim of extending the useful lifetime of materials by promoting recycling, extending the lifetime of products or phasing some of them out, all whilst lowering resource use and environmental impacts (Tisserant, et al., 2017; Milios, 2018). About 500 kilogrammes of municipal waste per capita are generated every year in the EU. These wastes contain large volumes of valuable materials for Europe's industrial base. Proper collection of waste is a pre-condition for their optimal recovery.

Improving the collection performance of waste collection systems (WCS), thus diverting more recyclable material towards the appropriate sorting facility and away from sending it for disposal is the obvious first step towards achieving the ambitious recycling targets proposed by the EU. For instance, common EU targets of recycling 75% of paper, 50% of plastic packaging, 50% aluminium, 70% ferrous metal and 70% glass by 2025 (increasing to 85%, 55%, 60%, 80% and 75% respectively by 2030) have been put in place (European Commission, 2018). Good regional practices have the potential to serve as good examples for other regions and go some way to achieving these targets. So far, however, results of existing studies of high performing WCS have not been effective enough in supporting the implementation of better-performing systems elsewhere. The main objective of the COLLECTORS project is to overcome this situation and to support decision-makers in shifting to better-performing collection system.

COLLECTORS will therefore:

1. Increase awareness of the collection potential by compiling, harmonising and presenting information on systems for paper and packaging waste (PPW), waste electrical and electronic equipment (WEEE) and construction and demotion waste (CDW) via an online information platform.

2. Improve decision-making on waste collection by the assessment of twelve good practices on their performance on:

   (1) quality of collected waste;

   (2) economics;

   (3) environment;

   (4) societal acceptance.

3. Stimulate successful implementation by capacity-building and policy support methods that will increase the technical and operational expertise of decision-makers on waste collection.

4. Engage citizens, decision-makers and other stakeholders throughout the project for validation of project results and to ensure the usability of COLLECTORS-output.

In relation to Work package 3, the COLLECTORS project covers the following waste streams and their associated materials/ categories:

- **PPW from private households (and similar sources):**
  - Paper & cardboard (both packaging and non-packaging)
  - Plastic packaging
  - Glass packaging
  - Metal packaging
  - Packaging made from composite material
- **WEEE from private households and similar sources:**
  - Small household appliances
  - Information technology (IT) equipment
  - Light bulbs
- **CDW with a focus on wastes that are managed by public authorities.**
  - Bricks
  - Insulation

- Sanitary ceramics
- Gypsum

1.2 Life Cycle Assessment

Life Cycle Assessment (LCA) is a technique used to quantify the environmental impacts of products and services over their lifetime. LCA modelling is comprised of four phases under the ISO 14040 framework (Standardisation, 2006): goal and scope definition, inventory analysis, impact assessment and interpretation (Figure 1). Almost all major decisions on the design of an LCA should be based on the initially defined **goal and scope** of the study. These decisions involve defining the functional unit upon which impacts will be assessed, as well as the system boundary for the LCA model. The functional unit is a measure of the function of the studied system and it provides a reference to which all the inputs and outputs can be related. This enables comparison of two or more different systems in order to determine which one is associated with the least environmental impacts. The next stage, **inventory analysis**, involves collecting all relevant data on the system modelled regarding its inputs and outputs, including emissions and waste disposal to establish a life cycle inventory. **Impact assessment** is then carried out during which scientifically defined characterisation factors, such as Global Warming Potential (GWP), are applied to different emissions and resource inputs to the production system in order to quantify its overall environmental impact for different impact categories, such as climate change, acidification, eutrophication, etc. Throughout all of these stages, the methodological choices made at each stage need to be systematically identified, qualified and evaluated in order to properly **interpret** the results.

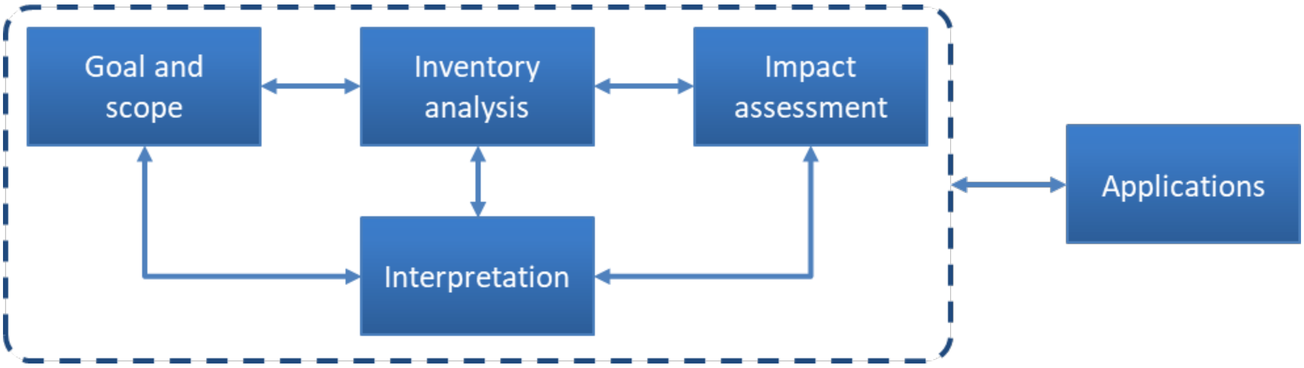

Figure 1: The fundamental stages of an LCA according to ISO 14040 (Standardisation, 2006).

1.3 Purpose of this report

While the European Commission supports LCA as the best framework for assessing a system's potential impact on the environment, there have been calls for more consistent data and a consensus on the best way to practice, apply, and interpret LCA methodologies across member states (European Commission, 2019; ILCD, 2010). These are goals of the Commission's European Platform on LCA, which aims for open communication and data sharing for businesses and governments. Strategies for streamlined models have been proposed before but have been criticised for lacking the transparency and consistency needed for large-scale analysis of systems with sparse data or at early stages of development. This is especially true of some WCS, where there is often a lack of primary data that can be provided by municipalities, and where the performance of recently established collection strategies is difficult to assess, especially in a methodological setup that enables cross-WCS comparisons. Next to a lack of data and comparability, another problem typically encountered are system boundaries. For example, the municipality may understand quite well what is happening in their system, but once waste is collected and sent to the next stage, their knowledge is limited and it is difficult for them to assess the consequences of their handling of the waste for the entire system. Therefore, in order to close data gaps, enabling fair comparisons of different WCS, and addressing the problem of limited system boundaries, the aim of this report is to present a generic methodology that can be used to assess the environmental performance and improvement options for waste collection systems across Europe.

To realize this, a practical methodology has been developed within Task 3.1 of the COLLECTORS project which can fill data gaps and enables the assessment of the environmental performance of WCS of specific municipalities. Since decisions at the WCS affect the quantity and quality of recycled materials and subsequently the share of virgin materials that can be replaced by recycled (secondary) materials, the system boundaries have been broadened to include not only the waste collection and sorting, but also the upstream production and the downstream recycling and treatment stages in the assessment. In this way, the consequences of decisions at the collection and sorting for the entire system can be assessed. The generic model proposed builds upon literature-derived data and data available from a widely accepted Life Cycle Inventory (LCI) database (ecoinvent). The approach is iterative in nature and data and assumptions from literature sources should be replaced with specific primary data, e.g. from the case municipality, wherever feasible, to reduce the uncertainty of the assessment. While this makes the study specific to a WCS, the broad system boundaries and the fact that large parts of the studied system are based on average data and assumptions for Europe ensure a high degree of comparability of assessments between different WCS.

The methodology will be applied in D3.3, which provides LCA results for 12 case studies that may be used as good examples of WCS. The practical recommendations shall be applied both on the level of individual cases and across all cases, providing thus specific and generic insights into environmental best practices for WCS.

2 Methodology

2.1 Goal and Scope

2.1.1 Goal

The goal of the LCA methodology presented in this report is to analyse holistically the environmental impacts associated with the processes involved in and affected by dedicated source separation WCS, including the production of the products, collection, sorting, the disposal and the recycling of material. The methodology is aimed at different waste streams, such as paper and packaging waste (PPW), waste electric and electronic equipment (WEEE) and construction and demolition waste (CDW). The methodology shall provide insight into the environmental performance of collection systems and the influential parameters during collection and sorting that affect both downstream recycling and treatment as well as upstream substitution of primary materials during production. The methodology is presented in such a way that it may be applied by expert LCA practitioners, waste companies or regional authorities alike.

Similarities and differences can be observed in the composition and management strategies of each individual *waste material* (e.g. paper) or *category* (e.g. electronic equipment such as information technology (IT) devices) within each *waste stream* (e.g. PPW, WEEE, CDW) between municipalities. By analysing the environmental performance per material, better insight into the performance of each municipality in terms of individual resource efficiency can be achieved. It is important that comparisons between municipalities are made upon the same quantity of a waste material or category (the functional unit of the LCA), e.g. “1 kg of waste paper”. In this report, we use the functional unit “1 kg of each waste material” from each waste stream. While this is consistent with functional units used in the ecoinvent database (Wernet, et al., 2016), relating the environmental impacts to “1 ton of each waste material” may be better in communicating with waste stakeholders. These values can be multiplied by the total quantity of generated waste for each material/category to obtain the overall environmental impact for each material/category, the sum of which will be the total environmental impact for that waste stream.

2.1.2 Scope

The scope of the LCA is to assess the waste management choices and the environmental implications of different waste streams. In order to capture the consequences of the quality and quantity of collected wastes for resource recovery and substitution, a broad system-perspective needs to be adopted. Therefore, the following life cycle stages shall be covered (Figure 2):

- primary production with possible substitution of virgin materials through closed-loop recycling;
- waste collection and sorting;
- open-loop recycling, and;
- disposal (including incineration and landfilling) with possible energy recovery.

The use phase of the materials before they become waste is excluded, as it can be assumed not to change as a result of decisions at the WCS. Where the ultimate fate of the materials is not clear due to a lack of data (e.g. as is common for WEEE) the environmental impacts associated with the treatment of this waste are not included within the scope of the model, although the production of these materials is still assessed.

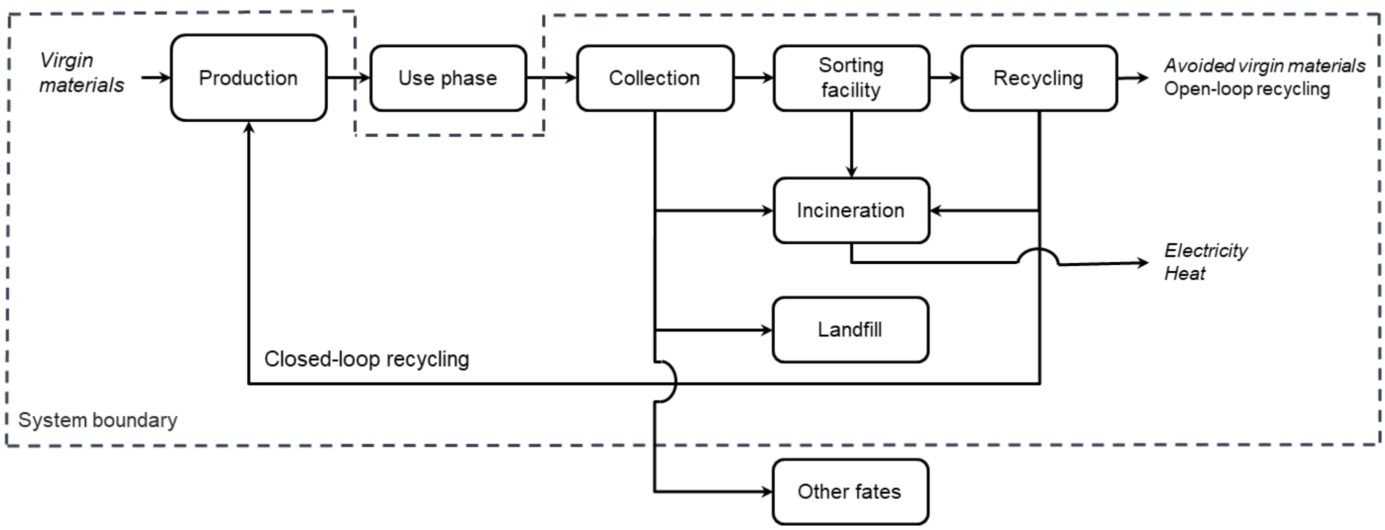

Figure 2: Flow diagram representing the generic life cycle phases covered by the LCA methodology assessing the environmental impacts of waste in the COLLECTORS project.

2.2 Inventory modelling

2.2.1 Data requirements and sources

Throughout the European Union, some WCS may provide detailed data to perform LCA analyses, however, other WCS may be characterized by very limited data availability. The challenge is to develop an LCA methodology that can be applied to WCS throughout the EU despite substantially different data availabilities. That is, even under data scarcity, the methodology should be able to capture the complexity of the WCS, including all the relevant management decisions along the life cycle, which are key to understanding the environmental impacts associated with each waste stream, assessing the environmental performance of WCS and giving recommendations for improvements. A summary of (typical) data requirements is given in Figure 3.

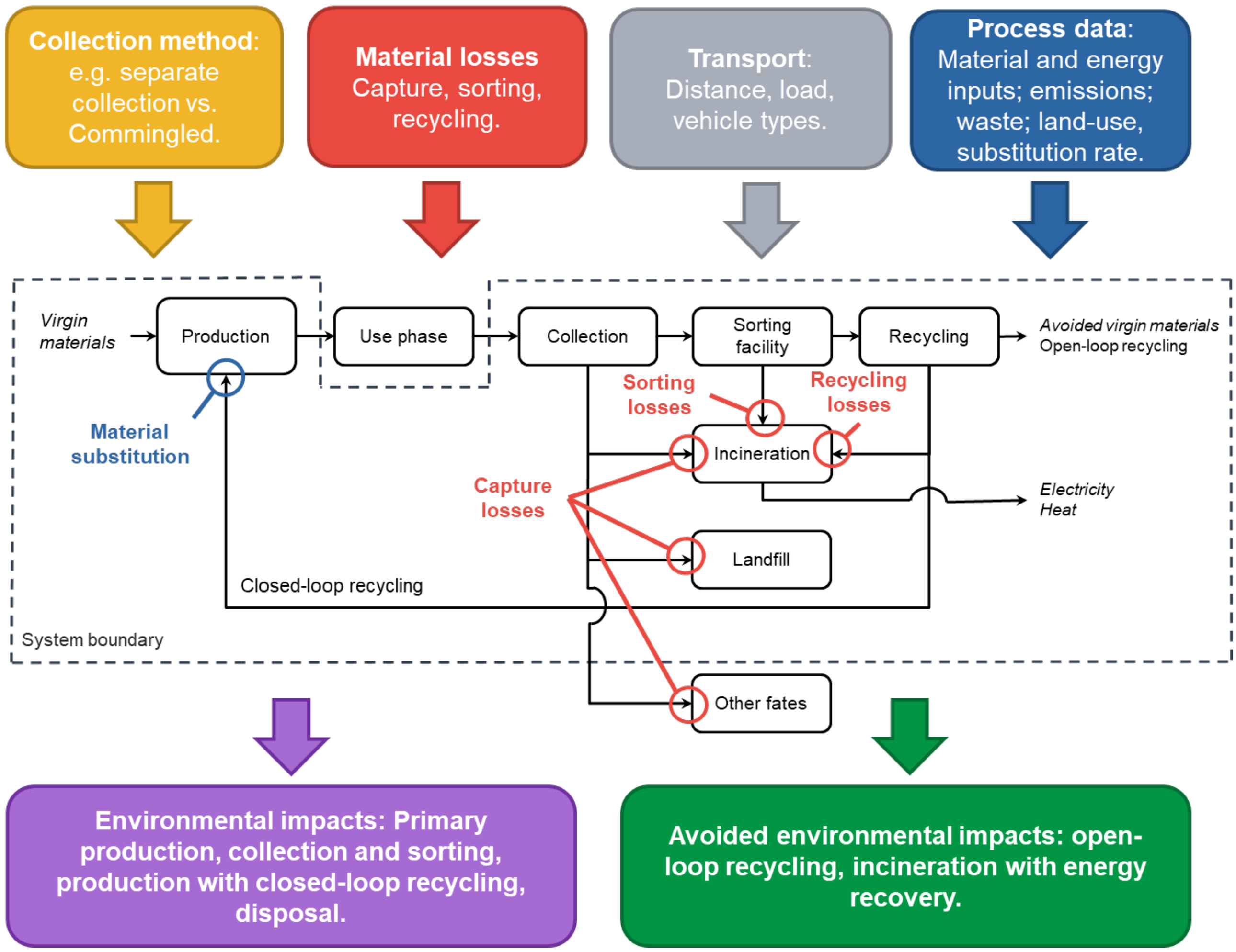

Figure 3: Flow diagram representing the life cycle phases covered by the methodology and the inputs and outputs of the model (adapted from Figure 2). Input data can be sourced from municipalities, compiled as part of the COLLECTORS project and/or various literature sources or life cycle inventory databases.

A consistent methodology such as this is necessary to make fair comparisons when performing LCA studies for different WCS. Three sources of data can be used to define the input parameters; in order of reducing relevance to the specific case studies, these are:

1. Data collected and provided directly by the municipalities for the purpose of LCA.
2. Data collected and compiled on the selected WCS in yearly reports or similar. Such data was gathered as part of work package 1 in the COLLECTORS project and is available online[1], although not sufficient by itself for the purpose of LCA.
3. Data available in the literature or life cycle inventory databases (e.g. regional or national level).

While case study specific data (sources 1 and 2) are the ideal basis for performing LCA based analyses of the onsite production processes, such data is often difficult to obtain and even then most likely incomplete, e.g. in terms of measured emissions. Background life cycle inventory (LCI) databases are made for this purpose and containing detailed process inventories representing average or typical data for the relevant life cycle stages included in our system boundaries (i.e. the production of products as well as collection, sorting, recycling and further treatment for the waste streams considered). The ecoinvent database (Wernet, et al., 2016) is the database of choice due to its high quality in terms of modelled detail, peer review process and transparency (e.g. unit process based). While this can provide the generic model, local data (sources 1 and 2) should be used wherever possible to adapt the model to a specific WCS.

2.2.2 Multi-functionality

Waste management systems are typically multi-functional systems. That is, on one hand they serve the management of waste, but on the other hand they recover secondary resources that can be used by other production processes. When a system serves several purposes, it is multi-functional and additional steps are required in order to be able to associate environmental impacts with the

[1] https://www.collectors2020.eu/tools/wcs-database/

different functions of the system. For example, municipal waste incineration serves the purpose of disposing of residual waste while producing energy from it. The ISO 14040 standard (ISO 14040, 2006) suggests the following procedure in order to deal with multi-functional systems:

- To avoid multi-functionality by further disaggregation of processes;
- To expand the system boundaries to include the additional functions of the system (system expansion approach), or to substitute co-products (avoided burdens approach);
- To partition processes, i.e. to use physical or other relations (e.g. revenues) to associate the inputs and outputs of a process with its different functions (allocation approach).

Further disaggregation is not an option for the systems considered here, which means that the systems are inherently multi-functional. The disadvantage of the system expansion approach is that functional units may become very confusing (e.g. instead of “1 kg of paper” the functional unit would have to be reformulated as “1 kg of paper and x kWh of electricity and y kWh of heat” co-produced from the incineration of paper going to disposal instead of recycling). Instead, we recommend the use of the avoided burdens approach, which retains simple functional units such as “1 kg of paper”, but at the same time considers the substitution of “x kWh of electricity” and “y kWh of heat”.

Net environmental impacts (E), of each impact category (i), associated with each functional unit can then be calculated following Equation 1 below. The avoided impacts due to secondary material in the open-loop recycling and the environmental impacts avoided due to energy generation should be reported as negative values. Avoided impacts may embody a large degree of uncertainty, related to what is actually replaced with the recycled materials, which is often not fully clear. For this reason, it is recommended to report these impacts separately. Furthermore, there may be large differences in energy recovery efficiencies between different incineration plants, and also in local energy and heat production profiles as compared to national averages. These uncertainties can be minimized by collecting as much primary data as possible about open-loop recycling and energy recovery for each municipality being assessed; this uncertainty should be kept in mind when interpreting the results. The sum of these avoided impacts is subtracted from the sum of the impacts associated with primary production, closed-loop recycling, collection, sorting and disposal.

$$E_{i\,[net]} = \left(E_{i\,[collection\ and\ sorting]} + E_{i\,[primary\ production]} + E_{i\,[\text{closed−loop recycling}]} + E_{i\,[disposal]}\right) - \left(E_{i\,[displaced\ energy\ production]} + E_{i\,[avoided\ impacts\ from\ open-loop\ recycling]}\right)$$

Equation 1

2.3 Material flow modelling

2.3.1 Production

The total amount of each material (produced for packaging, electrical equipment etc.) is determined by the demand for that material. Within the model presented in this study, material is produced from two systems defined by different material flows (F): primary production, which uses only virgin materials, and production with both virgin materials and recycled materials, i.e. closed-loop recycling (Equation 2). The proportion of each material produced from primary production and with closed-loop recycling is determined based on the material flow through the WCS; this, in turn, determines the total share of recycled material in PPM and ultimately the environmental impacts associated with production.

$$F_{material\ demand} = F_{primary\ production} + F_{closed-loop\ recycling}$$

Equation 2

The amount of each material that is produced and enters the use phase is equal to the amount of each material that leaves the use phase and becomes waste (Equation 3), i.e. steady-state is assumed.

$$F_{material\ demand} = F_{material\ waste}$$

Equation 3

2.3.2 Collection and sorting

The proportion of waste material collected in a dedicated separate WCS compared to the amount of waste material that is generated is defined by the capture rate of the system for that material. The “total material generated” is assessed via waste composition analysis (e.g. for PPW), or via measured quantities put on the market if such data is available for the municipality being assessed. The capture rate of each waste type should be calculated for each case study using equation 4:

$$Capture\ rate = \frac{Material\ collected}{Total\ material\ generated}$$

Equation 4

The total material generated can be calculated as amount ending up in residual waste plus the separately collected amount (approach used for PPW) or, if such data is not available, based on national averages for waste generation per capita (approach used for WEEE).

Once collected, the material is then transported to a sorting facility. The average transport load, transport distance (tkm) and vehicle type are determined for each material to determine the impacts associated with the collection and transportation of the waste. Upon arrival, the material is sorted and pretreated before recycling can take place. The system inputs and outputs associated with the sorting stage, such as the energy requirements of the processing, can be based on European averages for each material modelled in the ecoinvent database, if local data is not available.

2.3.3 Material losses

The proportion of material produced from primary production and from production with closed-loop recycling is determined based on the material flow through the WCS. Before the material can be recycled, losses (l) occur at various stages of the system (Equation 5). Following the production and the use phases, material is collected as part of a separate WCS or in the residual waste or has another fate. Materials that enter the residual waste or have another fate are classed as material losses ($l_{capture}$). This is measured by the capture rate (Equation 4; $l_{capture}$ = 1 – capture rate), i.e. the percentage of the generated material that is collected separately in a dedicated WCS. Thus, the amount of material entering the source separation WCS is determined by how proficiently target material is separated from residual waste or other material flows.

After collection, materials are transported to sorting facilities before being subjected to two stages of treatment, defined here as sorting and recycling. Further material losses occur during these stages. At the sorting stage, material is lost due to sorting inefficiencies and contamination ($l_{sorting}$). The level of contamination in turn may differ between collection methods (Eriksen, et al., 2018). According to the amendment to the EU directive on paper and packaging waste, the calculation of recycling rates should be based on the weight of a material entering the recycling operation (European Commission, 2018); thus, the amounts of each material that would be lost at the stage are considered. In addition, losses occur at the recycling stage due recycling inefficiencies ($l_{recycling}$); these losses are also important in determining how much material is ultimately recycled, however these losses are not considered for example in the calculation of the PPW recycling rates (European Commission, 2018). All material losses are illustrated on Figure 3 (section 2.2)

$$F_{recycled\ material} = \left(\left(1 - l_{capture}\right) * \left(1 - l_{sorting}\right) * \left(1 - l_{recycling}\right)\right) * F_{material\ waste}$$

Equation 5

2.3.4 Substitution rate

Recycled materials do not completely replace the virgin materials in the production of a material, and this is due to various factors. For instance, the quality of each recycled material is dependent on the contamination of the waste stream, as well as the inherent deterioration in the properties of the materials undergoing the recycling process (paper fibre shortening, plastic polymer chain scission and cross-linking, etc.). The amount of virgin material that can be replaced via closed-loop recycling is also effected by the economic competitiveness of recycled material within the free market (Gala, et al., 2015). Another factor is legislation that limits the amount of material that can be recycled due to product safety issues. The proportion of recycled material that can substitute virgin material is defined by the substitution rate ($r_{substitution}$) of each material (i.e. Appendix, Table A2).

The requirement of virgin materials in the production of secondary materials makes it difficult to define "recycling" in a generic way for each type of material that is considered in the COLLECTORS project. For instance, the recycling process for paper involves releasing the fibres from waste paper and combining these fibres with virgin fibres. It could be argued that recycling of plastic, on the other hand, ends with the production of flakes before this material is combined with virgin materials. In this project, the closed-loop recycling of material includes the input of virgin material (see section 2.4). Hence, closed-loop recycling includes the impacts associated with the recovering the secondary material from waste, combining it with virgin materials in the production of the recycled material, as well as the impacts associated with the production of the virgin materials themselves.

The demand for each material is determined based on steady-state analysis (Equation 3), i.e. the amount of material production is equal to the amount of waste generated for that material. Thus, the maximum amount of recycled material that can substitute virgin materials in the production of a specific material ($F_{subsitution,\ max}$) is determined based on the total amount of waste generated and the substitution rate (Equation 6). The proportion of recycled material that can substitute virgin material via closed-loop recycling is defined by the substitution rate. In some cases, more material may be recycled if it is economically viable to do so. The demand for each material is hence calculated based on the following points:

- Steady-state analysis i.e. the amount of material required is equal to the amount of that waste material that is generated, determined from the data collected in this project and specific to each municipality.
- The market demand for recycled material compared to virgin material, determined from literature e.g. the demand for specific qualities of each plastic polymer or the amount of recycled aluminium the packaging industry uses.
- The physical limitations of recycled material e.g. material quality reductions compared to virgin material, determined from literature.

If the demand for the recycled material is met, then 100% of the products can be made using recycled material included at the substitution rate. Where the demand for each recycled material is met, the surplus recycled material is used to replace virgin material in products with uses that differ from what the original material was used for. This can be defined as open-loop recycling (see section 2.3.5).

$$F_{substitution,\ max} = F_{material} * r_{substitution}$$

Equation 6

2.3.5 Recycling

Within the model, closed-loop recycling of material occurs when the material is of sufficient quality and where there is demand for it from that materials original market (i.e. the maximum substitution amount has not been achieved) (Equation 5). The quality of each recycled material should be considered; this is dependent on the contamination of the waste stream, as well as the inherent deterioration of the properties of the materials undergoing the recycling process (Gala, et al., 2015). Where the amount of a recycled material exceeds the demand for it from its original market, or the recycled material is not of sufficient quality to be used in that market, it is assumed to displace virgin materials for the use in other applications. This has been referred to here as open-loop recycling (Equation 6). The list of potential products that can be produced from each recycled material, and the materials these products would be conventionally made from, is extensive. In the analysis presented here, material entering the open-loop recycling is assumed to avoid the production of the same material, of equal quality, from virgin materials. Hence, for most materials considered in this report, the difference between the impacts associated with producing the material from virgin materials and the impacts associated with the recycling process is accredited to the system. In some cases, entirely different raw materials may be replaced by a recycled material. Thus, the impacts associated with open-loop recycling must be regarded as indicative of the potential avoided impacts associated with the collected material only.

$$F_{closed-loop\ recycling} = MIN(F_{substitution,\ max}, F_{recycled\ material})$$

Equation 7

$$F_{open-loop\ recycling} = \begin{cases} F_{recycled\ material} - F_{substitution\ ,max}, & if\ F_{recycled\ material} > F_{substitution,\ max} \\ 0, & otherwise \end{cases}$$

Equation 8

2.3.6 Disposal

Materials that are not collected in the source separation WCS (e.g. entering residual waste or other waste flows), or are lost during the sorting and recycling processed may enter the disposal stage. Waste entering this stage can either be landfilled or incinerated. If the proportion of residual waste that is incinerated is known, this should be applied to the model. Otherwise the proportion of the residual waste that is sent to landfill and the proportion of residual waste that is presumed to be incinerated in each case study can be based on national averages (Eurostat, 2019). Energy that is recovered at the incineration stage from burning target materials (e.g. PPW materials), can be assumed to replace conventional energy production for a given municipality and this is accredited to the system. The impacts associated with conventional energy production, and hence the avoided impacts associated with energy recovery, should be based on the local situation or national averages for that municipality if no specific primary information is available. In some cases (e.g. WEEE), materials enter complementary material flows with unknown fates. Where the fate of a certain quantity of a material is unknown, the environmental impacts associated with this material cannot be calculated in a meaningful way. Hence the impacts associated with the disposal of these materials is considered to be outside the model system boundaries (Figure 2).

The material that is not captured at the collection stage, and instead enters the residual waste, is disposed of either in landfill or via incineration. The entirety of material lost at the sorting and recycling stages can be assumed to be sent for incineration with energy recovery. The electricity and heat production that can be achieved via the incineration process for each material type is based on information found within the ecoinvent database (Wernet, et al., 2016). The energy captured during the incineration process (both electricity and heat) can displace the equivalent energy production based on inputs in corresponding national averages. The environmental impacts of incinerating each material are added to the total impacts of the system, whereas the total impacts associated with the avoided energy production based on European averages are subtracted from the total impacts.

2.4 Impact assessment

The impacts associated with the functional unit (1 kg of each waste type), for each stage and for each case study can be reported in relation to different environmental impact categories. In LCA, midpoint and endpoint indicators are distinguished. Along the cause-effect chain, i.e. from the emission of a substance to the environment to its environmental damage, midpoint indicators are more closely related to the emission of a substance than to the damage, while endpoint indicators are related to the damage. An illustrative example for a cause-effect pathway is the emission of greenhouse gases, which results in an increase concentration of that gas in the atmosphere, which in turn results in higher radiative forcing (a commonly chosen midpoint indicator), which in turn leads to a temperature increase, which in turn leads to climate change with adverse effects (the damage) for human well-being, biodiversity, etc. While the damage has greater societal relevance, it is associated with much greater uncertainty. While midpoint indicators such as radiative forcing have less direct societal relevance, their advantage is that they represent changes in the environment that can be calculated with high certainty. For this reason, the ISO 14040 standard as well as other important literature (e.g. the International Reference Life Cycle Data System (ILCD) (Hauschild, et al., 2013)) recommend the use of midpoint indicators over endpoint indicators. Nevertheless, practitioners may choose to go further and also report endpoint indicators as well as the results of normalization and weighting exercises (although ISO 14040 conform studies should not contain weighted results).

Within the COLLECTORS project, we report environmental impacts at the midpoint level for 6 different impact categories, based on the expected types of impact on the environment (Skals, et al., 2007; Arena, et al., 2004; Lopes, et al., 2003). These categories are: global warming potential (GWP), fossil resource depletion potential (FDP), freshwater eutrophication potential (FEP), marine eutrophication potential (MEP), terrestrial acidification potential (TAP) and marine ecotoxicity potential (METP). Within the case study presented below we show only the results for climate change (GWP), while the full results for all case studies are reported in our deliverable D3.3.

2.5 Interpretation

2.5.1 Contribution analysis

Interpretation is the LCA phase in which the findings of either the inventory analysis or the impact assessment, or both, are combined consistent with the defined goal and scope in order to reach conclusions and recommendations.

For each of the environmental impact categories assessed, the total impact value associated with each stage of the system is calculated for each waste material.

- *Production*: The impacts associated with production can be broken up into that which is produced via primary production and that which is produced via closed-loop recycling. Alternatively, the production stage may just be reported as one result without distinguishing the impacts associated with production via closed-loop recycling and primary production.

- The *primary production* includes the impacts associated with the production of the materials from virgin materials only (Table A1, Appendix).
- The *closed-loop recycling* includes the impacts associated with the production of the materials from a mix of virgin materials and recycled material defined by the substitution rate (Table A2, Appendix); hence, the inputs to the recycling steps for each material are included in the impacts reported for closed-loop recycling.

- The *collection and sorting stage*: includes the impacts associated with the transportation of the waste and the inputs to the sorting facilities.
- The *disposal* stage: includes all the associated impacts of incinerating and landfilling the waste.
- The *open-loop recycling* stage: represents the difference between the impacts associated with producing materials from virgin materials and the impacts associated with producing the open-loop recycled material.
- The *energy recovery* stage: the avoided impacts of equivalent conventional energy production associated with the energy recovery during incineration, are reported as separate stages, see the appendix in D3.3 for full details.

The environmental impacts associated with each stage of the WCS can be calculated, the sum of which is the net environmental impact for the functional unit. In this way it is possible to determine the relative contribution of each stage to the total impact of the system, e.g. the proportion of the environmental impact for a certain impact category that is attributed to the collection and sorting stage. Each stage is interesting for different reasons and separating the impacts in this way allows the practitioner to examine where impacts are concentrated and what would be the best strategies for reducing the overall environmental impacts of the system. For instance, improving the sorting or recycling efficiency may have a big influence on one material, whereas the largest improvement for another material may result from improving the collection. Furthermore, the results of the LCA for some of the stages are inherently more uncertain than the impacts associated with other stages. For instance, the impacts of the materials entering closed-loop recycling are better known than the avoided impacts associated with open-loop recycling, where the list of materials that can be replaced for a given recycled material is extensive. This means separating the impacts associated with these stages is important to the contribution analysis.

2.5.2 Sensitivity analysis

Sensitivity analysis is a method for predicting the outcome of a decision if a situation turns out to be different compared to the key predictions. It helps in identifying how dependent the output is on a particular input value. A sensitivity analysis should be performed in the LCA to identify any assumptions and parameters influencing the outputs of the models for each case study. This can be done by identifying assumptions made in the models and running the model with alternative parameters. Typically this is done by adjusting certain parameters one by one to see the influence changing that parameter has on each environmental impact category. For the purpose of the COLLECTORS project, this will be performed for the parameters that influence the collection performance of the WCS.

It is widely acknowledged in the literature that the level of contamination associated with the collection method can affect the quality of the recycled material. To test this, the sorting efficiency and the rejection levels (due to contamination) of each material can be adjusted to reflect the range of material loss that might be expected at the sorting facilities (Eriksen, et al., 2018; Miranda, et al., 2013). If a range in the efficiencies have been reported by given municipality or at the national level, this information may be used within the sensitivity analysis. The effects of landfilling and incinerating the material at the disposal stage, as well as the energy production profiles (avoided by the energy recovery stage) should be considered by changing the proportions of waste sent to landfill and for incineration based on the specific situation in EU member states.

Practitioners should keep in mind what is important in their assessment; the more variables that are considered between any WCS, the more difficult it may become to identify causality without also carrying out a sensitivity analysis that reflects this complexity.

2.5.3 Consistency checks

The interpretation of the impacts associated with each stage of the system should be checked for consistency, to determine whether the assumptions, methods and data are consistent with the goal and scope. Differences in data sources and accuracy, geography/technology/time-related coverage, and data age should be considered. Data quality is important to study especially related to the most relevant processes that cause the highest impacts; using different data sets may change results dramatically. Can any of the data obtained through various literature sources or life cycle inventory databases be replaced by primary data from the municipality? If so, the primary data should always be considered. The study should also be subjected to a completeness check. For this a constructivist approach should be taken, i.e. the results should be shared with experts and other stakeholders, and comparison with other studies should be made where possible in order to validate the study.

3 Application to a case study

3.1 Goal and scope

Here, a case study is presented for the purpose of illustrating the methodology outlined in this report. For more details on the processes used to model the WCS and for a more comprehensive analysis of this case study, refer to D3.3.

3.1.1 Goal

In this report, the PPW WCS in Parma, Italy, is assessed as a case study. This is to show an example of how the methodology outlined can be used to determine the impacts associated with a waste stream such as paper and packaging. The goal of the study is thus to assess the environmental impacts associated with the stages of PPW, i.e. plastics, glass, paper, metal, and composite materials, in Parma, Italy.

3.1.2 Scope

The scope is identical to the scope as defined in section 2.1.2 , i.e. the following life cycle stages are modelled: primary production, collection and sorting, recycling (closed-loop and open-loop), disposal and incineration with energy recovery. The environmental impacts associated with the production of each paper and packaging material, the collection and sorting of the waste generated, and the fate of the materials are all considered within the system boundary. PPW is produced from both virgin and recycled material, the proportions of which are dependent upon the capture rate of each material at the collection stage, the material losses at the sorting and the recycling stages, and the demand for each recycled material. The use stage is not included within the scope of the analysis, as it can be assumed that it would not be affected by improvements in collection. The WCS includes all collected waste that is separated from residual waste by households in Parma and did not assume any mechanical recovery of PPW from the residual waste after collection. The functional unit is 1 kg of each material waste generated: paper, plastic, glass and metal.

3.2 Inventory analysis

3.2.1 Primary production

3.2.1.1 Paper

Following the steady-state assumption proposed in the methodology in this report, 18013 tonnes of paper were generated in Parma, including non-packaging and packaging paper, cardboard and the carton board recovered from composite material (Pivnenko, et al., 2016; FAO, 2018). The primary production of paper includes wood handling and processing (e.g. mechanical pulping), paper production, on-site energy use and internal waste water treatment (Wernet, et al., 2016).

3.2.1.2 Plastic

7660 tonnes of plastic were reported to be generated in Parma. Plastic packaging can be divided into different types of polymer: polyethylene terephthalate (PET); high density polyethylene (HDPE); low density polyethylene (LDPE); polypropylene (PP), and; polystyrene (PS). Data for the primary production of these polymers are derived from the eco-profiles of the European plastics industry (Plastics Europe, 2019). The environmental impacts of primary production are based on aggregated data for all processes from raw material extraction until each polymer is produced up until the point the material may be assembled into a packaging product. The inputs and outputs up until each polymer is produced is based on European averages, including the material, energy and infrastructure needed. PET is produced out of purified terephthalic acid and ethylene glycol. HDPE is made via the polymerization of ethylene under normal pressure and temperature. LDPE is made via the polymerization out of ethylene at high pressure and high temperature. Polystyrene is made via the polymerization of ethylene and benzene by free radical processes. Polypropylene is made via the polymerization of propylene.

3.2.1.3 Glass

9807 tonnes of glass were reported to be generated in Parma. Three types of packaging glass are considered in this report: white, green and brown. Most packaging glass is produced with cullet (recycled glass) input. However primary production of glass is necessary to fill the gap where not enough glass is recycled to meet the demand for cullet. The primary production of glass includes material and energy inputs, water consumption, emissions to air and water, waste production and infrastructure based on European averages.

Packaging glass is produced in a two stage moulding process with pressing and blowing techniques. The whole process is fully automatic and consists of five different stages: production of a molten glass piece (gob) with correct weight and temperature; forming of the primary shape in a first mould (blank mould) with compressed air pressure; transfer to the final mould (finish mould); blowing the container with compressed air, and; further post forming processes. The melting process is the central one. As the first glass forming material, sand, has a very high melting point. Soda as a fluxing agent is used to reduce the melting temperature. When heating soda, this is decomposed into sodium oxide, the fluxing agent, and into CO_2 that is released. Metal oxides in form of limestone ($CaCO_3$ that decomposes to CaO), dolomite, and feldspar are used to improve the hardness and chemical resistance of glass.

3.2.1.4 Metal

2394 tonnes of metal were reported to be generated in Parma, of which 75% is assumed to be aluminium and 25% is assumed to be steel (tinplate) (Eurostat, 2016). Molten aluminium is produced from an electrolytic process and tapped from reduction cells into a holding furnace and heated to approximately 750°C using natural gas as a fuel. Alloying elements, such as magnesium, silicon and manganese, for additional strength, corrosion resistance and other properties, are added to the aluminium. It is typically at this point in the process that recovered aluminium for closed-loop recycling is added, but since this dataset represents primary production, remelting is excluded. During furnace charging and preparation, aluminium dross (a thick liquid or solid phase) forms at the surface of molten aluminium. This mixture of aluminium oxides is remelted to recover the aluminium that would otherwise be lost. Metallurgical analysis verifies that the metal meets customer specifications before the metal is cast into products of specific dimensions, before being weighed, bundled and strapped ready for transport. The steel consists of sheets of steel, coated with a thin layer of tin, made by rolling the steel in a rolling mill. As with aluminium, the inputs and outputs of the steel making process and casting process without the addition of scrap is applied for the primary production process.

3.2.1.5 Composite material

445 tonnes of packaging made out of composite material was generated in Parma. This material is composed of carton board (75%), polyethylene (PE) (21%) and aluminium (4%) (Pretz & Pikhard, 2010). The environmental impacts associated with composite material (the production, as well as the other stages of the life cycle such as sorting recycling and disposal) are thus attributed to paper, plastic and metal in these proportions respectively.

3.2.2 Substitution / substitutability of primary materials

The substitution rates of the materials used were based on EU averages defined in the literature (Table A1, Appendix).

3.2.2.1 Paper

Virgin pulp and recovered fibres are not of equivalent quality; thus, it is a common practice to counteract this loss of quality by adding virgin pulp to the recycled material of the different material types in various proportions. The substitution rates for the different paper types (i.e. the amount of recycled fibres in each paper type) in closed-loop recycling are presumed to be 83% for newsprint, 29% for other non-packaging paper, 84% for the packaging paper and cardboard, and 43% for carton board (Gala, et al., 2015; Sevigné-Itoiz, et al., 2015; Rigamonti, et al., 2009).

3.2.2.2 Plastic

The quality losses of the recycled polymers in the closed-loop system are estimated based on substitution values in the literature (Van Eygen, et al., 2018). The substitution rates for PET, HDPE, LDPE, PP and PS recycled polymers are 93%, 73%, 61%, 75% and 67% of the virgin material in the closed-loop recycling respectively.

3.2.2.3 Glass

The substitution rate in the closed-loop recycling of glass is limited by the maximum colour contamination limits for container glass cullet and the market demand for each colour. These are 0.61%, 0.84% and 0.55% for white, green and brown glass respectively.

3.2.2.4 Metal

Unlike paper and plastic, the amount of times metal may be recycled is infinite in theory. However, the maximum amount of material that can enter closed-loop recycling is limited by the market demand. Thus, the substitution rate of aluminium and steel packaging is presumed to be 75% and 50% respectively (Gala, et al., 2015).

3.2.3 Collection and sorting

Data was provided on the fuel type and fuel use for the transport of each waste material. Based on the fuel efficiency of the vehicles used, the impacts associated with transporting each material can be estimated based on data provided by the municipality of Parma. The inputs to the sorting facility are specific to each type of material collected but are based on European averages available in the ecoinvent database.

3.2.3.1 Paper

Paper is collected separately from all other PPW materials in Parma. The capture rate is 0.81. Paper is collected and sorted into different grades before being processed to release the fibres for use in closed-loop and open-loop recycling (Gala, et al., 2015). The contribution of each grade to the production of recycled fibres in paper production are based on transfer coefficients for the production processes reported in the literature (Pivnenko, et al., 2016).

3.2.3.2 Plastic

Plastic is collected as part of a PMD (plastics, metal and drinks cartons) commingling collection system in Parma. The capture rate was 0.69. The material is cleaned in order to remove any unwanted debris. The plastic then needs to be homogenized as to increase the material quality. Sink-float separation is used to separate the polymers: HDPE has a lower specific density than PET, meaning that these plastic polymers can be separated in this way. However, HDPE has a similar specific density to PP. In this case, near infrared radiation techniques can be used. The plastics are heated and shredded so that they become pellets which can be used in manufacturing. Considerable losses of each type of polymer occurs at the sorting facilities due to contamination, these are calculated based on the study presented by (Eriksen, et al., 2018).

3.2.3.3 Glass

Glass is separated from all other PPW materials by households. The capture rate is 0.93. Further sorting takes place after the glass is crushed into cullet, ready to be sent for recycling.

3.2.3.4 Metal

As discussed above, metal is commingled with plastic and drinks cartons (composite material) in Parma. The capture rate of metal in Parma is 0.33. Magnets remove steel packaging from the PMD commingled waste. Nonferrous metals are separated using an eddy current separator. The metals are crushed and baled, ready to be sent to be recycled.

3.2.4 Closed-loop recycling

3.2.4.1 Paper

The datasets used to assess the production of paper via closed-loop recycling are based on the European averages for the production of each type of material considered in this report using deinked pulp from wastepaper. The impacts associated with wood handling for the incorporation of virgin material, mechanical pulping and bleaching, deinking of wastepaper (where necessary, e.g. newsprint), paper production, energy requirements and internal wastewater treatment are included in the life cycle inventory. The pulp created from the paper fibres recovered from composite material is concentrated and also used for the production of new paper products (Pretz & Pikhard, 2010). Enough paper is collected to produce 100% of the demand for newsprint, cardboard and carton board via closed-loop recycling.

3.2.4.2 Plastic

A reduction in the quality of the plastic polymers occurs during the recycling process (Gala, et al., 2015; van der Harst & Potting, 2014). Thus, each time plastic is recycled, additional virgin materials must be added to help improve the integrity of the material. For each type of recovered plastic, the amount of high, medium and low-quality polymers that can be recycled are calculated. Data on the recycling of the polymers are derived from the eco-profiles of the European plastics industry

(Plastics Europe, 2019). Plastic recovered from composite material is assumed to be incinerated with energy recovery.

3.2.4.3 Glass

The recycling rate for each type of cullet is based on averages stated in (Rodriguez Vieitez, et al., 2011). The recycling of glass involves mixing cullet with raw materials (sand) before remelting the material in a furnace. For white glass, decolouring agents are added. For green glass, colouring agents are added. The glass is then mechanically blown into new glass packaging products following the same steps as in primary production. The recovered glass that is not of suitable quality to produce packaging, based on the assumed contamination level of the waste stream, enters open-loop recycling.

3.2.4.4 Metal

Melting and pre-processing yields should be considered in the resource recovery efficiency (Brimacombe, et al., 2005; Niero & Olsen, 2016; Løvik & Müller, 2016). Recovered metal reenters the production at the metal packaging in the holding furnace where it is remelted and combined with virgin materials. The aluminium recovered from composite material is used as a bauxite substitute in cement (Pretz & Pikhard, 2010) (Section 3.2.2).

3.2.5 Open-loop recycling

In the analysis presented here, recycled material entering the open-loop recycling is assumed to avoid the production of the same material, of equal quality, from virgin materials. Hence, the difference between the impacts associated with producing the material from virgin materials and the impacts associated with the recycling process is accredited to the system.

As more recycled fibres are produced for newsprint, cardboard and carton board than is demanded from closed-loop recycling in Parma, the surplus material enters open-loop recycling. Only medium quality plastic polymers enter open-loop recycling and this is because there is assumed to be no demand for these polymers for the production of packaging (Eriksen, et al., 2018). The demand for glass from the glass packaging industry is not met, however a certain amount of material is of insufficient quality to be used to make new packaging glass and entered open-loop recycling. An insufficient amount of metal is collected in order to meet the demand from closed-loop recycling and so collected metal did not enter open-loop recycling.

3.2.6 Disposal

If no regional data is available, the proportion of landfilling and incineration can be based on national averages (Eurostat, 2019). The entirety of material that is rejected at the sorting stage can be assumed to be sent for incineration with energy recovery. The electricity and heat production that can be achieved via the incineration process for each material type is based on information found within the ecoinvent database (Wernet, et al., 2016). The energy captured during the incineration process can displace the equivalent energy production based on inputs in corresponding Italian national averages (Appendix, Table A3. The environmental impacts of incinerating each material are added to the total impacts of the system, whereas the total impacts associated with the avoided energy production based on European averages are subtracted from the total impacts.

Based on the Italian national average, 34% of the residual waste is incinerated in Parma, therefore 34% of each material entering the residual waste is assumed to be incinerated with energy recovery and 66% is assumed to be landfilled. All material lost at the sorting stage, due to contamination and sorting inefficiencies, and at the recycling stage is assumed to be incinerated with energy recovery.

3.3 Impact assessment

Figure 4 presents an example of how the methodology described above can be applied to a case study, and how the impacts of each life cycle stage can be presented. The municipality of Parma is used as a case in point. The total GWP for paper, plastic, glass and metal in Parma is 17, 21, 62 and 13 million kg of CO_2 equivalent (CO_2-eq.), respectively. Other Environmental impact categories are considered in D3.3. Per kg of waste generated (the functional unit), metal has the highest net GWP and plastic has the second highest net GWP (Figure 4). A considerable proportion of the GWP of plastic is the result of incineration, but this also leads to the most avoided GWP associated with the energy recovery at incineration of any material. In contrast, the amount of energy recovered from metal is negligible.

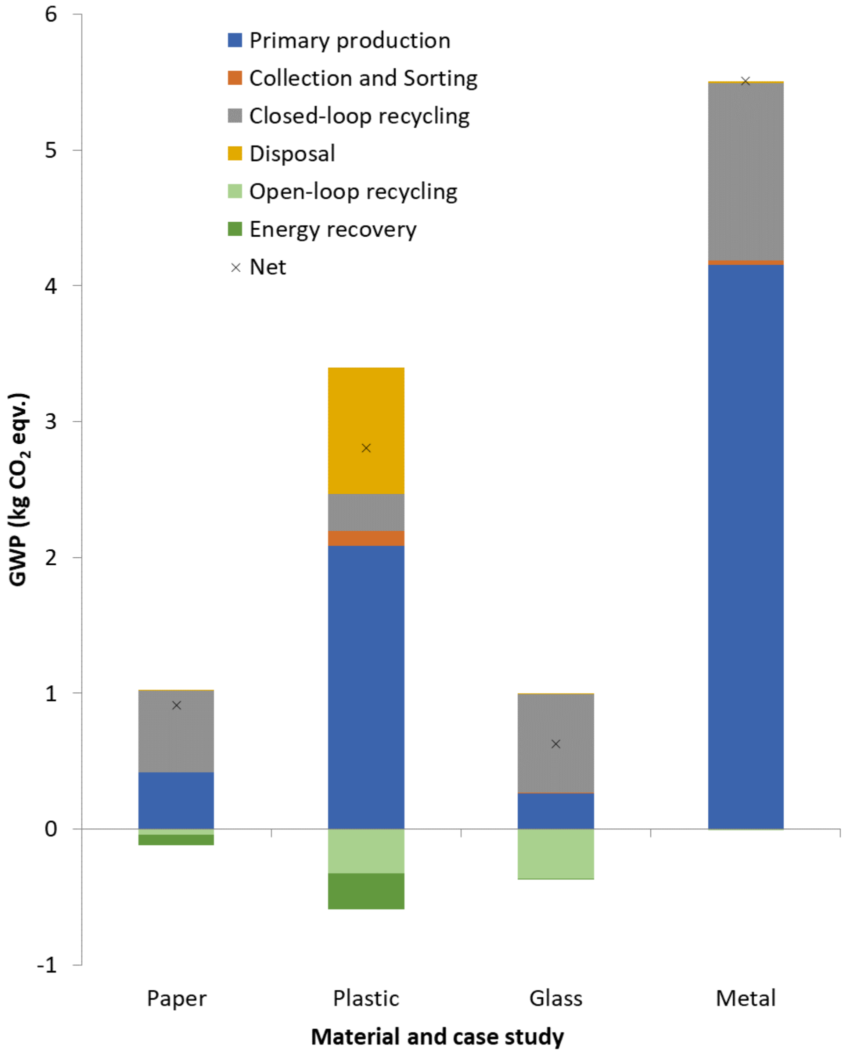

Figure 4. Example of results for PPW LCA analysis. Data relates to 1 kg of each waste type collected in Parma.

3.4 Interpretation

3.4.1 Contribution analysis

The relative contribution of each stage to the total GWP impact of paper and packaging can be seen in Figure 4. From the results of the LCA of paper and packaging in Parma, the main impacts are seen in the production stages, whereas only 1.8% of the total impact is associated with the collection and sorting of PPW. Paper, plastic and glass enter both closed-loop and open-loop recycling. This is because the recycled material exceeded the demand for recycled material for a given material, or some of the recycled material was at a lower quality than what is required by closed-loop recycling.

For metal, the material is not assumed to be downcycled, and the demand for the material from closed-loop recycling is not met. Only metal that is recovered from the composite material is assumed to enter open-loop recycling; as the avoided GWP associated with this material is negligible, the avoided impacts for metal was relatively small for Parma.

Although 28% of the plastic can be produced via closed-loop recycling in Parma (i.e. 28% of the plastic produced incorporates recycled material at the substitution rate), it accounts for only 12% of the GWP associated with the production of plastic. By recycling plastic, the primary production can be reduced and thus the environmental impact associated with plastic packaging production can be reduced. For paper, 73% can be produced via closed-loop recycling, accounting for 59% of the GWP associated with production. For glass, 80% can be produced via closed-loop recycling, accounting for 73% of the GWP associated with production. For glass, 46% can be produced via closed-loop recycling, accounting for 24% of the GWP associated with production. Hence, increasing the recycling rate via better waste management results in a lower overall impact for each material.

3.4.2 Sensitivity analysis

A sensitivity analysis should be performed in the LCA to identify any assumptions and parameters influencing the outputs of the model for each case study. Sensitivity has been performed on the parameters that influence the collection performance of the PPW WCS in Parma (Table 1). By adjusting certain parameters one by one, the influence of changing each parameter on each of the environmental impact categories can be assessed – here the effects on GWP are reported (see D3.3 for a more comprehensive sensitivity assessment). The sensitivity analysis performed here shows the percentage change in the total impacts associated with paper and packaging when a parameter is increased by 10%, whereby a negative change relates to a reduction in environmental impact.

The table indicates where the improvements made in the PPW WCS in Parma are most effective. In terms of increasing the capture rate of the different target materials, increasing the capture rate of plastic would have the largest reduction in greenhouse gas associated with packaging. Improving plastic sorting efficiency shows the most potential for reducing greenhouse emissions of all the parameters. As shown in D3.3, it is important to do a full analysis for all environmental impact categories in order to identify trade-off situations (e.g. when change in the system leads to better climate change performance at the expense of higher impacts in another impact category). In this way the LCA of different case studies can be used by stakeholders to determine where improvements should be made in the WCS in order to reduce the overall impact.

TABLE 1: SENSITIVITY ANALYSIS RESULTS FOR THE MUNICIPALITY OF PARMA. MATERIAL LOSSES ARE REDUCED BY 10% INDIVIDUALLY AT EACH STAGE OF THE LIFE CYCLE.

Parameter	Material	Change in GWP
Collection	Plastic	-0.89%
	Paper	-0.85%
	Composite material	0.05%
	Metal	-0.86%
	Glass	-0.87%
	Total	**-3.42%**
Sorting	Plastic	-1.78%
	Paper	-0.01%
	Glass	-0.53%
	Metal	-0.60%
	Total	**-2.92%**
Recycling	Plastic	-2.43%
	Paper	0.23%
	Total	**-2.20%**
Gross Total		**-9.31%**

In Parma, reducing capture losses had the largest effect on the environmental performance of the system compared to reducing sorting or recycling losses. Increasing capture rates translates into collecting a larger proportion of each waste material generated with the same level of contamination. All materials followed this trend, except for plastic, where it is shown that greater environmental impact reductions can be achieved by reducing losses at the sorting and recycling stages. Reduced losses at the sorting and recycling stages can be achieved by reducing the contamination level of waste at the collection stage, as well as by increasing post collection recovery efficiency, which will be achieved via systemic waste management improvements, e.g. via better packaging design and technological advancements in sorting and recycling. Reduced losses of paper at the recycling stage is associated with increased GWP. This is due to the fact paper is a renewable resource. Since less paper is incinerated if more is recycled, less conventional energy production is avoided.

4 Reflections on the methodology

4.1 Advantages

4.1.1 Broad systemic perspective captures key parameters for a circular economy

The LCA methodology outlined in this report can be implemented to perform environmental assessment on WCS with a broad systemic perspective. In this way, the circularity of the system and the far-reaching consequences of choices at the collection stage can be evaluated. This methodology allows stakeholders to easily identify where making further improvements to WCS will make the most environmental impact reductions. Local context should be considered and where this is not possible results may provide only general guidelines, but this would still be useful for pointing out hotspots or points where future efforts should be focused. When combined with a cost benefit analysis (Task 3.2 and deliverable 3.2 of the COLLECTORS project) and/or social assessments, a more comprehensive understanding can be gained; such research makes it possible to identify the best strategies for implementing best practice, following good examples of WCS in Europe. Thus, the methodology enables us to better predict the outcomes, in terms of environmental impacts, that may be expected in return for investments into WCS.

4.1.2 Consequences of decisions at the WCS can be analysed

The methodology enables the environmental consequences of decisions made at the collection stage to be captured, even those that appear downstream of collection, such as material losses due to contamination and sorting inefficiency and thus the amount of material that can be recycled in either a closed-loop or open-loop.

4.1.3 Method works with varying data quality

The methodology that is proposed in this report can work for varying data quality. In general, there is a lack of primary data provided by municipalities that is needed to perform detailed LCAs. The performance of recently established WCS may not been fully assessed or the municipality may have only limited their knowledge on what happens to the waste after it is collected. This methodology allows LCA to performed in a streamlined way, bridging data gaps. Whilst performing an LCA with limited specific data on a system may not be ideal, it at least allows a broader range of stakeholders to better understand how waste collections may be improved in general.

4.1.4 Comparability across case studies

Finally, the presented methodology enables a fair comparison across different case studies, if the same system boundaries and other modelling assumptions are applied. The ability to compare case studies will help to better understand the key issues that need to be improved across WCS and, therefore, generic aspects where changes could be incentivized by policy or other instruments. While it should be said that due to the complexity of LCA models, it is difficult to claim that LCA models are ever fully correct and comparable, using a common methodology, should definitely much improve the current situation that is characterized by case-by-case LCA studies that are largely incomparable due to differences in system boundaries and other key assumptions.

4.2 Limitations

4.2.1 Value of the results and potential learnings depend on data availability

The LCA of the different WCS modelled following the guidance in this report will be limited by the data available to the practitioner. In many cases, information on the fate of the individual materials after they are collected by a municipality is limited. The methodology presented here bridges data gaps based on a more general model which provides a broad system prospective that incorporates necessary literature-derived data. This means the results may not necessarily reflect the absolute impacts of a particular municipality. On the other hand, the generic model captures general key parameters in WCS, which may already provide valuable insights to stakeholders.

4.2.2 Complementary flows not included

Complementary flows are not included in this methodology, as the they fall outside the scope of the COLLECTORS project. As discussed, the recovery of PPW from residual waste post collection is not considered. In addition, WEEE that is not collected in a dedicated WCS and processed appropriately may have any number of fates, from simply being stored by the consumer for many years (hibernation), to being disposed of in the residual waste, to being exported to a different country where its valuable parts may be salvaged before the rest of the material is incinerated. With better data on the fate of the WEEE, the methodology could be expanded to better reflect the environmental consequences of complementary flows.

4.2.3 Optimization beyond WCS needed for a circular economy

Material use may be extended, or the energy consumption of the product may be reduced, via better product design. Whilst the use phase may be important in terms of the circular economy, the purpose of the COLLECTORS project was to assess the implications of WCS only. Thus, whilst the methodology presented here allows us to better understand the impacts of producing each material and the effects of improving collection, it does not provide us with any information regarding how the use phase effects the impacts. The model methodology could be expanded to include this, which is particularly interesting with the perspective of comparing alternatives, e.g. different packaging options for the same products. However this was not within the scope of the COLLECTORS project.

4.2.4 Avoided impacts for open-loop recycling

It should be noted that, whilst the fate of materials that remain in the system via closed-loop recycling is clear within the methodology presented here, the fate of the materials that enter open-loop recycling is less obvious. For the purpose of this project, the difference between the impacts associated with producing the same material (of the same quality) from virgin materials and the impacts associated with the recycling process is accredited to the system as “open-loop recycling”. In some cases, other materials may be replaced by a recycled material that are made from entirely different raw materials. For instance, recycled plastic may be used in the production of items conventionally made entirely from wood or both wood and metal, e.g. a park bench. In this case, the model can be adapted so that the difference between the impacts associated with producing the recycled material and producing the different material that is being replaced can be accredited to the system. Thus, the open-loop recycling must be regarded as only indicative of the potential avoided impacts associated with the collected material. These avoided impacts should be reported as a separate stage in the results.

5 Conclusions

This report provides a practical methodology and thus guidance for assessing the environmental performance of WCS in Europe. Key advantages of the methodology are that i) it adopts broad system boundaries to capture both the upstream and downstream consequences of decisions made at the collection and sorting stages of WCS, ii) it builds upon average European data that can be made more specific on a case-by-case basis, but prevent important data gaps if no local data is available, and iii) this setup enables a high degree of comparability among case studies.

Hence, this report outlines a strategy for streamlined models by providing a broad system prospective that incorporates necessary literature-derived data, sourced as part of a LCA meta-analysis, which can fill data gaps when assessing the environmental impacts of the WCS of specific municipalities. This should thus be a step forward towards the European Commission's aim to create more consensus on the best way to practice, apply, and interpret LCA methodologies as stated by the Commission's European Platform on LCA (European Commission, 2019).

The methodology is iterative in nature, in that higher levels of complexity may be added to the model whilst comparisons can still be made between different WCS. For instance, if a municipality can provide more detailed information about the sorting efficiency of their waste recovery after collection, then this data may be applied to the model, replacing the European averages for the type of system that is employed. Furthermore, extra steps may be added in the model to better represent certain aspects of the WCS. However, the more specific data is added, the more it becomes difficult to relate the differences to broad general characteristics of the systems.

Applying the methodology can generate both case specific and generic insights into environmental best practices for WCS. By evaluating the circularity and environmental implications of waste collection, it can be shown at which point in the system improvements need to be made in order to facilitate the transition to a circular economy. The methodology that has been explained here is applied in D3.3 of the COLLECTORS project to 12 case studies (5 PPW, 5 WEEE and 2 CDW) that have been selected because they represent good collection practices or offer unique learning opportunities for other municipalities.

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Appendix

TABLE A1: ENVIRONMENTAL IMPACTS (GLOBAL WARMING POTENTIAL) OF PRIMARY PRODUCTION OF EACH MATERIAL PER KG (NO SUBSTITUTION OF VIRGIN MATERIAL).

Material	Material type	Substitution rate	GWP
Paper	Newsprint	0.00	1.47
	Other (non-packaging)	0.00	1.23
	Graphic paper	0.00	1.55
	Paper (packaging)	0.00	1.42
	Cardboard	0.00	1.01
	Carton board	0.00	0.61
Plastic	PS	0.00	4.46
	PET	0.00	3.12
	HDPE	0.00	2.01
	LDPE	0.00	2.81
	PP	0.00	2.05
Glass	Clear	0.00	1.29
	Green	0.00	1.30
	Brown	0.00	1.30
Metal	Aluminium	0.00	8.14
	Steel (Tinplate)	0.00	5.86

TABLE A2: ENVIRONMENTAL IMPACTS (GLOBAL WARMING POTENTIAL) OF THE PRODUCTION WITH CLOSED-LOOP RECYCLING OF EACH MATERIAL PER KG (VIRGIN MATERIAL REPLACED AT THE SUBSTITUTION RATE)

Material	Material type	Substitution rate	GWP
Paper	Newsprint	0.83	1.11
	Other (non-packaging)	0.29	0.63
	Graphic paper	0.29	0.79
	Paper (packaging)	0.84	0.73
	Cardboard	0.84	0.83
	Carton board	0.43	0.54
Plastic	PS	0.67	1.84
	PET	0.93	1.43
	HDPE	0.73	0.81
	LDPE	0.61	1.26
	PP	0.75	0.80
Glass	Clear	0.61	0.92
	Green	0.84	0.86
	Brown	0.55	0.94
Metal	Aluminium	0.75	2.74
	Steel (Tinplate)	0.50	3.51

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