Centre for Sustainability

COLLECTORS
WASTE COLLECTION SYSTEMS ASSESSED AND GOOD PRACTICES IDENTIFIED

COLLECTORS

Work package 3

Quantification of costs and benefits

Deliverable 3.3: Report of recommendations for improvement of single systems and optimum operation conditions of waste collection systems

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Credits

Disclaimer

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Summary

This report provides the environmental assessments of 12 case studies on waste collection in Europe, including 5 paper and packaging waste (PPW) cases, 5 waste electrical and electronic equipment (WEEE) cases and 2 construction and demolition waste (CDW) cases. The report applies the Life Cycle Assessment (LCA) methodology presented in D3.1 to the 12 case studies as part of Work Package 3 (Task 3.3) of the COLLECTORS project. We adopt a broad systemic perspective to capture not only the potential environmental impacts generated by the waste collection systems (WCS) themselves, but also the consequences of quality and quantity of collected wastes for resource recovery and substitution of primary resources. Thus, the model covers the life cycle of the materials used in paper and packaging, electrical and electronic, and construction products: i.e. primary production, waste collection and sorting, as well as recycling and disposal. We also include closed and open-loop recycling as options to close material loops and substitute primary materials through recycled materials. The substitution potential of secondary materials is determined based on the assumption of a steady-state system and the limits to the recyclability of materials (e.g. paper cannot be recycled indefinitely, but instead always requires a certain amount of virgin fibres). The use phase of products is excluded, as it can be assumed not to change as a result of decisions at the WCS. Data was provided by stakeholders (interviews and questionnaires) and published data (i.e. scientific literature, national and regional reports, and a life cycle inventory database).

We find that there is a substantial potential to reduce the environmental impacts for all materials covered in this report through a better management of waste streams. The key to this is efficiency along the waste management chain, i.e. high capture rates, as well as high sorting and recycling efficiencies. In addition to increasing the quantities of waste, attention should be given to high value recycling, which is closely linked to quality considerations in the collection, sorting and recycling of wastes, but also ideally to product design. Individual results and recommendations for the 12 case studies are provided in the report, although these results should be interpreted with some caution as local data was only available from the collection stage and thus the lifecycle perspective that is provided in this report relies on average data for upstream and downstream lifecycle stages.

Contents

List of abbreviations

CAS	civic amenity site
CDW	construction and demolition waste
EU	European Union
FEP	fresh water eutrophication potential
FDP	fossil resource depletion potential
GWP	global warming potential
IT	information technology (electronic devices)
LCA	life cycle assessment
MEP	marine eutrophication potential
METP	marine ecotoxicity potential
PAYT	pay-as-you-throw
PMD	paper, metal and drinks cartons
PPW	paper and packaging waste
PRO	producer responsibility organisation
TAP	terrestrial acidification potential
WCS	waste collection systems
WEEE	waste electrical and electronic equipment
WP	work package

1 Introduction

1.1The importance of waste management

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, whilst lowering resource use and environmental impacts (Tisserant, et al., 2017; Milios, 2018). About 500 kg 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 material sorting facility and treatment processes, 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). Under the EU WEEE directive vendors have an obligation to recover end-of-life devices. A target of 85% (based on the average of electrical and electronic equipment put on the market in the last 3 years) or 65% of WEEE produced that year needs to be collected by 2025 (European Commission, 2012).

1.2The COLLECTORS project

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 waste collection systems 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.

The **objectives** of the COLLECTORS project are to:

1. Increase awareness of the collection potential by compiling, harmonising and presenting information on systems for PPW, WEEE and 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.

Thereby, the COLLECTORS project is specifically focussing on the following waste streams:

- **Paper and packaging waste (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.

These materials represent all the paper and packaging materials targeted by different municipalities in accordance with the packaging and packaging waste directive (European Commission, 2018)

- **Waste Electrical and Electronic Equipment (WEEE) from private households and similar sources;**

- Small household appliances;
- Information technology (IT) equipment;
- Light bulbs;

This is only a few categories of WEEE. These were considered due to the high quantities of these materials that are still being thrown in residual waste.

- **Construction and demolition waste (CDW) with a focus on wastes that are managed by public authorities.**

- Bricks
- Insulation
- Sanitary ceramics
- Gypsum

1.3 Aim of this report

The objective of Work package 3 (WP3, Quantification of costs and benefits) of the COLLECTORS project is to evaluate the environmental and economic performance of 12 case studies selected as good examples of WCS in Europe. **The aim of this report is to assess the environmental impacts of the WCS of the selected case studies using the life cycle assessment (LCA) methodology and to provide recommendations for improvements and operation conditions.** This report is a deliverable of Task 3.1 "LCA meta-analyses of 12 selected case studies and guidance document".

1.4 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 (ISO 14040, 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.

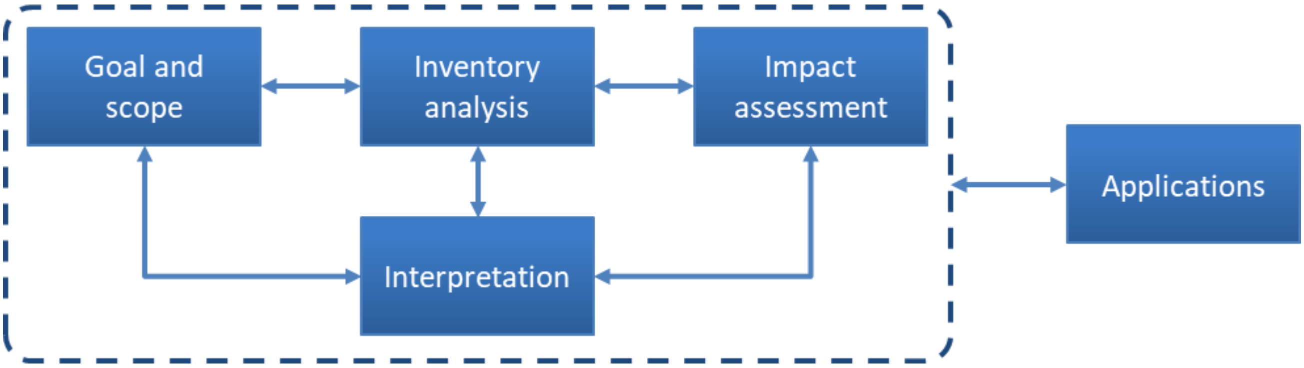

Figure 1: The fundamental stages of an LCA according to ISO 14040 (ISO 14040, 2006).

LCA is, therefore, the right methodology to quantify the impacts of a product or service holistically over its lifetime. This means that the whole system can be considered within predefined boundaries, e.g. raw material extraction, manufacture and waste management. Product distribution and the use phase may also be considered. LCA can be used for identifying environmental hotspots within systems and for comparisons between alternative systems.

In this report, LCA is performed for each case study by following the methodical guidance developed in D3.1, which broadens the scope of the assessment from the collection phase to the full life cycle, but excludes the use phase of products. This approach provides the basis for an assessment of the consequences of choices at the collection stage for the lifecycle environmental impacts associated with paper and packaging, electrical and electronic, and construction materials and products.

1.5Case study selection

Data collection took the form of consultation with stakeholders and an extensive literature review of national reports and isolated case studies. The characteristics of the municipalities included in this study varied in terms of area size, population density, level of tourism, GDP and total waste generated. Data were collected on each of these characteristics, as well as on the performance of the WCS employed by each municipality with regards to each of the waste streams included within the scope of the study.

For PPW, data were compiled on the WCS of 135 municipalities from 24 EU member states. For WEEE, 73 municipalities from 18 member states were considered. For CDW, 34 municipalities from 17 member states were considered. In total, 5 PPW, 5 WEEE and 2 CDW were selected from the municipalities sampled (Figure 2-4). The selection of these 12 case studies was based on in-depth analyses in WP2 and dialogue with involved stakeholders as part of WP3. To do this, a participatory approach with local and regional authorities was used with the objective of building the methodology for a multiple-criteria decision making approach, from which all the case studies could be ranked (see COLLECTORS D1.3). For PPW, the capture rates of each waste were weighted in relation to importance as concluded by the focus groups; all capture rates received similar weightings, with plastic being regarded as slightly more important than the others. For WEEE, the criteria deemed most important was the total WEEE collected per inhabitant and the share of WEEE in mixed residual waste. For CDW, the number of inhabitants per civic amenity site (CAS) was the most important factor. Case studies were then selected based on their high ranking and characteristics. Lastly, an assessment of data availability and willingness to cooperate was performed, in order to ensure cooperation and relevant data in the case studies (to this end we've had to drop and reselect some cases – which is discussed in Deliverable 7.1). This task performs a LCA to gain insight on the environmental performance of these WCS and the influential parameters as outlined in D3.1, thus gathering more data that is applicable to a broad range of stakeholders.

Figure 2: The PPW caste studies: Parma (Italy), Tubbergen (The Netherlands), Gent (Belgium), Berlin (Germany) and Rennes (France).

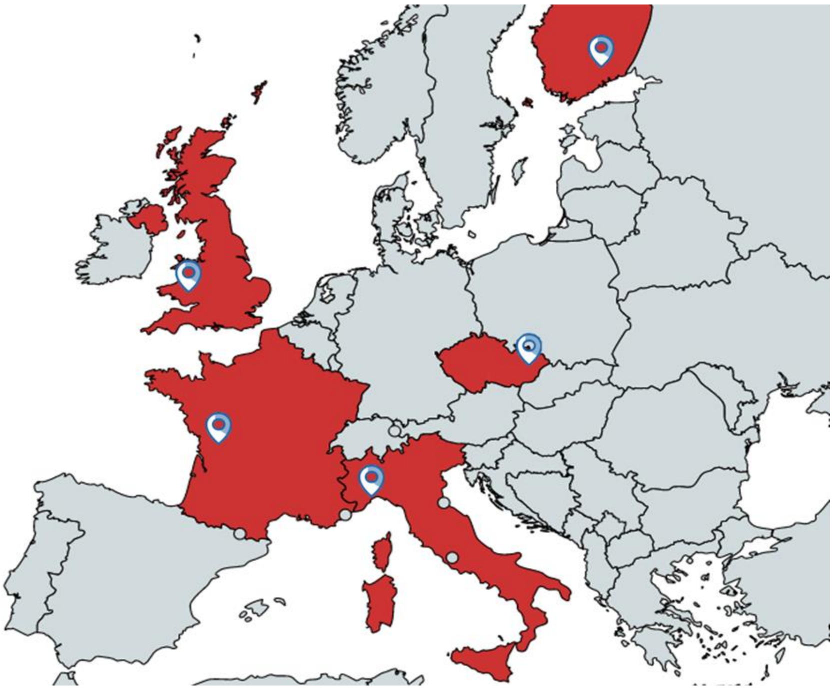

Figure 3: The WEEE case studies: Pembrokeshire (UK), Genova (Italy), Cyclad (France), Vienna (Austria) and Helsinki (Finland).

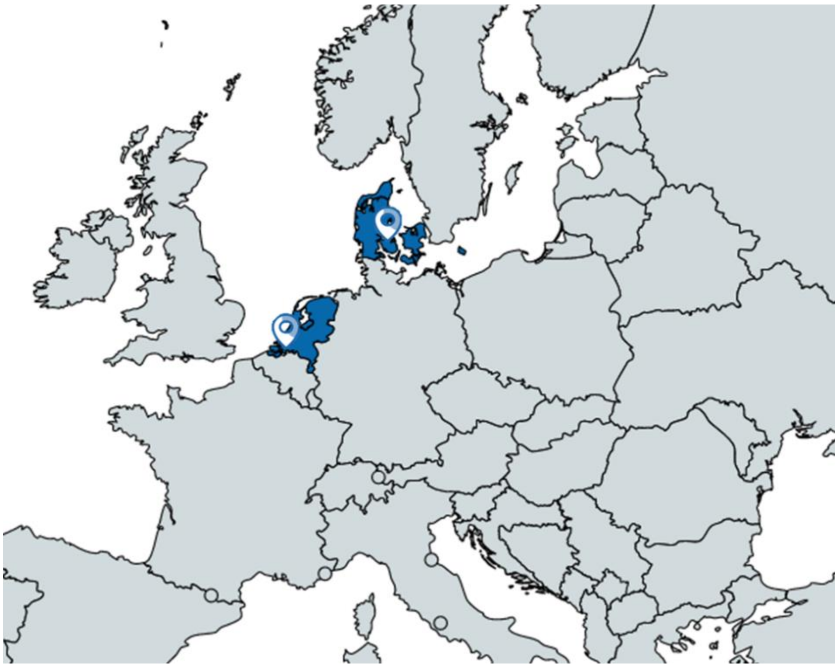

Figure 4: The CDW case studies: Odense (Denmark) and Reimerswaal (The Netherlands).

1.6Case study backgrounds

1.6.1 Paper and packaging waste case studies

1.6.1.1 Parma

Parma is a city located in Northern Italy at the foot of the Apennines with around 194,000 inhabitants. The region is Italy's top waste producer with 107,026 tonnes in 2016. Parma is leading the transition towards Zero Waste in the region (Zero Waste Europe, 2018). Currently Parma collects 78% of the generated PPW separately from residual waste and has an estimated recycling rate of 69%. Parma employs a "pay-as-you-throw" (PAYT) system, in which residents pay for the amount of paper, plastic, metal and composite materials and residual waste that is collected at the curb side. Residents are encouraged to place less PPW in the residual waste stream via a financial incentive (see D3.2 for more on PAYT in the cost benefit analysis).

The PPW collection in Parma can be described as a PMD commingling method. This means plastic, metal and composite material ("drinks cartons") are collected together and this is so called "light weight packaging waste" by the municipality. Paper and glass are collected separately. The residual waste, paper, and PMD are collected at the curb side, using home containers and bags. Several bring points (glass) and eight eco-stations (automated CAS where citizens can bring all waste except residual) are also available. The collected residual waste is transported to the sorting and incineration facility of Irens Ambiente, located in Parma. Paper waste is transported to the paper recycler Ghirardi in Parma. White and coloured glass is sent to Furlotti. The PMD stream is sent to the Oppimitti or Masotina recycling facility.

1.6.1.2 Tubbergen

The municipality of Tubbergen is a small municipality (21,142 inhabitants) in the rural east side of the Netherlands, close to the border of Germany. 9,514 tonnes of MSW was generated in 2016. Tubbergen currently collects 94% of the generated PPW separately from the residual waste and has an estimated recycling rate of 85%.

The municipality effectively manages its waste by working together with the regional waste management company NV ROVA. This includes the collection and processing of different types of waste: organic waste (door-to-door collection), PMD, residual waste and paper (door-to-door collection, bring points, CAS) and glass (bring points). PMD, paper and cardboard and residual waste are all collected using either mini containers or shared containers. Glass is collected using 42 communal containers. PMD is transported to Attero in Wijster, the residual waste is transported to Twence in Hengelo.

Following “Afvalloos Twente” (waste-less Twente), Tubbergen has opted for the ambitious waste policy plan “Van Afval naar Grondstof, Van Idee naar Aanpak, Van Betalen naar Belonen” (from waste to raw material, from idea to approach, from payment to reward) to achieve a residual waste amount of only 50 kg per inhabitant per year by 2030. To achieve this, various measures were implemented in 2015 (facilitating the transition towards a complete PAYT system) which have resulted in a sharp decline in residual waste and a significant increase in separately collected waste (a decrease in residual waste from 200+ kg per inhabitant per year in 2015 to 63 kg in 2017, 65 kg in 2018) (Gemeente Tubbergen and ROVA, 2017). The achieved separation percentage in 2017 was already above the national standard of 75% for 2020.

1.6.1.3 Gent

Gent is a port city in northwest Belgium with almost 250,000 inhabitants. 76,374 tonnes of MSW was generated in 2017. Currently Gent collects 85% of the generated PPW separately from residual waste and has an estimated recycling rate of 77%.

The inter-municipality of IVAGO serves both the city of Gent and the neighbouring municipality of Destelbergen. IVAGO has its own collection equipment but works together with private company SUEZ to complement the collection services. Since the introduction of the PAYT principle in 1998, the collection system for household waste in Gent has remained practically unchanged (IVAGO, 2017). However, continuous improvements have been implemented over the years, which have resulted in large reductions in the amount of residual waste ('restafval') collected and the amount of illegal dumping ('sluikstorten'), while PMD, glass and paper capture rates have stayed fairly constant.

IVAGO collects residual waste, PMD, glass and paper and cardboard separately throughout the city and has defined three zones which each have their own collection approach:

- **Zone C**: Container-zone (waste collected in containers);
- **Zone Z**: Zakken-zone (waste collected in bags);
- **Zone S**: Sorteerpunten-zone (waste collected at a sorting point).

Depending on the zone the waste is collected in containers, bags or at bring points. In addition, Gent has 6 civic amenity sites where citizens can discard of their waste.

The glass waste from Gent is transported to High 5 Glass sorting and GRL Glass Sorting for sorting. Gent's Paper waste is sorted by Stora Enso Paper Sorting. The residual waste is sent to IVAGO's incinerator. Lastly, PMD is sorted by Suez in the R&R BE North facility.

1.6.1.4 Berlin

Berlin is a large capital city with over 3.5 million inhabitants. 1,350,457 tonnes of MSW was generated in 2016. Currently Berlin collects 59% of the generated PPW separately from residual waste and has an estimated recycling rate of 54%.

Berlin has implemented a PAYT-based waste collection system focused on the separate collection of PPW. The waste collection is organised and carried out by the Berliner Stadtreinigungsbetrieben.

This includes the waste materials considered for the so-called Dual Systems (German producer responsibility scheme for the packaging waste): paper, cartons, glass and light packaging. Glass is collected separately (white, green, brown) and Berlin has 1,467 bring points for glass waste. Berlin also employs a PMD commingling method; PMD is collected in yellow shared containers and wheelie bins at 27,600 bring points throughout the city. Additionally, it is possible to get specific household waste bags (6€ per bag) at civic amenity sites, which can be ordered in case of an unusual higher amount of waste. Berlin has 15 civic amenity sites. Co-mingled waste is collected using household waste bins (‘Hausmülltonne’). There are 5 different sizes available, which can be ordered depending on the amount of household waste arising in a specific household (varying from 60 – 1100 litres) (Senatsverwaltung für Stadtentwicklung und Umwelt Berlin, 2015). The frequency of collection is bi-weekly. Berlin also has a deposit scheme, whereby plastic bottles can be returned to machines in exchange for store credit.

The first entry point for paper waste is the sorting facility WUB Wertstoff-Union Berlin GmbH, where the collected paper is sorted. Different material types are for example carton board, mixed paper and de-inking capable paper. During this step, all non-paper material is removed. Plastic waste from the PMD entry point is sorted at the ALBA Recycling GmbH sorting facility, providing the material to the market for subsequent recycling steps.

1.6.1.5 Rennes

Rennes is a city in the east of Brittany in north-western France with 438,865 inhabitants. 204,552 tonnes of MSW was generated in 2017. Currently Rennes collects 55% of the generated PPW separately from residual waste and has an estimated recycling rate of 44%.

Waste is managed by “Rennes Métropole”, operated by various subcontractors: Sita Ouest and La Feuille d'érable (Household and recyclable waste collection), Tribord (Door-to-door vegetable waste and bulky waste collection). The collection method used is PMD + Fibres commingling. Thus plastic, metal, composite materials and paper are collected together; residents put these items in yellow recycling bins and bring points. Glass is collected separately at bring points but the different colours are mixed.

1.6.2 Waste electrical and electronic equipment case studies

1.6.2.1 Pembrokeshire

Pembrokeshire is a coastal county in the south-west of Wales and therefore part of the UK, with around 125,000 citizens living on 1,590 km^2, i.e. 79 inhabitants/km^2. In Wales the GDP per capita amounted to £19,002 (Pembrokeshire County Council, 2019). Wales follows UK legislation in terms of recycling and waste collection. The United Kingdom in turn follows the European WEEE directive introduced in 2012 on WEEE collection (European Commission, 2012). The directives main concerns was the introduction of the "Producer Responsibility" principle, obliging producers (importers, producers, retailers) to have a capture rate of 85% (based on the average of electrical and electronic equipment put on the market in the last 3 years) or 65% of electrical and electronic waste produced that year by 2025. Also, they are to be financially responsible for at least the transport of WEEE from the communal collection points to the sorting facilities.

The collection of WEEE in Pembrokeshire, in contrast to other municipalities in Europe is not organized via a Producer Responsibility Organisation (PRO); no WEEE is collected from households directly. REPIC is the contracted PRO for the region and is in charge of bringing the waste from the collection points to the material recovery plants. Residents are obliged and encouraged to bring their potential electronic waste to one of 8 collection sites. The capture rate of small WEEE, IT and lamps have increased in the last couple of years by more than 30%. Investments into school education programs, research and development funding, as well as public awareness campaigns ("Don't bin it, bring it") have likely contributed to this increase. These programs have been established in cooperation with WRAP, a charity organization dedicated to improving circular economy (My Recycling Wales, 2018). Recently, reuse centres such as "The green shed" and "Pembrokeshire Remakery" have been built.

1.6.2.2 Helsinki

Finland has 5.43 million inhabitants with an average population density of less than 18 inhabitants/km^2. The distance between the southernmost to the northernmost points of Finland is almost 1,200 km. The majority of Finns live in the southern and western parts of the country. The most populous area is the Helsinki Capital Region, including the cities of Helsinki, Espoo, Vantaa, Kauniainen and Kirkkonummi in the southern coast, with about 1.2 million inhabitants in total covering 1,157 km^2, i.e. 1,037 inhabitants/km^2. 79% of the population lives in multi-family houses, 21% in (semi)detached houses. The average household size is 1.9 persons. The GDP amounts to 50,741 €/cap.

In Finland, the collection of WEEE is arranged mainly as a permanent collection; in 2011, approximately 450 collection points existed around the country. Permanent collection points are in most cases collectively financed by the producer associations, provided by the municipality and, in some cases, by private companies or social enterprises. Private users and households can bring their end-of-life products to the collection points free of charge (Ylä-Mella, et al., 2014).

However, permanent collection systems are not always efficient, due to e.g. long distances and low quantities of returned devices. Therefore, WEEE collection in Finland is also organized as a mobile collection in the 50 smallest or least populous municipalities. In the Helsinki region, mobile collection of small WEEE is organized twice a year, in addition to the permanent bring points and civic amenity site (CAS). While one round is organized by the regional waste management company HSY, the other one is organized by the regional recycling centre (Kierrätyskeskus). The recycling centre collects only functional devices (169 tons/year).

In addition, the amounts of WEEE received in retail stores have also increased. Since 2007, the overall WEEE capture rate in Finland has exceeded 9 kg/inhab/year ranking third best in the European Union. The transportation of WEEE from reception points and registered stores to the regional treatment plants is managed by the producer associations. The logistics services are typically sourced from private regional operators. At the collection points, the WEEE is divided into four different categories with lamps and batteries being collected separately: cooling devices (fridge and freezers), large domestic appliances, small WEEE and IT. Lamps are collected separately by FLIP Association, a producer organization responsible for the producer responsibility of lamps falling within the scope of the WEEE directive.

At the regional sorting plants, WEEE is separated based on brands, not on product categories or source, for different product cooperatives, weighed, and sorted into reusable and not reusable materials. Functional devices are manually separated and directed for preparation for reuse. The rest of the WEEE is sorted out according to WEEE categories and is pre-treated before sending to the various treatment plants for final treatment. The companies offering sorting and dismantling services to producers associations are typically social economy enterprises but a few private companies also exist in the field. Some of the dismantling and pre-treatment plants provide final treatment services for particular WEEE categories; however, most of the sorted and pre-treated WEEE is forwarded to detached recovery and/or final treatment plants located mainly in Finland. While all WEEE of a certain brand is treated at the same pre-treatment stations, all WEEE of the same category are sent to the same final recycling plants.

The main challenges of WEEE collection in the Helsinki region are related to the size of permanent collection points. In the smallest, the physical space for collection cages is limited and the amounts of returned devices is low. Therefore, mobile collection and retail stores as WEEE bring points were introduced in 2013. The use of the retailers take-back option has been very limited in Finland due to strong resistance the from Finnish retail businesses. However, in accordance with the Directive 2012/19/EU, the retailer take-back option has been extended throughout Finland. Since 2013, electrical and electronic devices can also be returned to the retailers in association with buying a new, corresponding device. Furthermore, small WEEE and lamps (all dimensions no more than 25 cm) can also be returned with no purchase obligation to electronics shops with area larger than 200 m^2 or to grocery shops of 1000 m^2 minimum. Additionally, fluorescent lamps and LEDs, as well as portable batteries and accumulators, can also be returned to the retail shops with no purchasing obligations.

There are no exact guidelines for the implementation of in-store reception, however, shops are required to finance and organise the place, the requisites, and the work contributions needed to receive WEEE. Distributors may forward the received WEEE to the reception points of official collection networks by themselves or, alternatively, they may enrol in a distributors register in order to obtain free unloading services financed by producers associations.

4,126 tonnes of WEEE (3.5 kg / cap) are collected at the CAS and 8,957 tonnes of WEEE (7.6 kg / cap) are collected at 2,000+ retail bring points. Another reason for the increased collection quantities is the improved reporting and reporting accuracy thanks to new treatment operators.

1.6.2.3 Genova

Genova is the capital of the Italian region Liguria and the sixth-largest city in Italy. It is located in Northern Italy on the Gulf of Genoa in the Ligurian Sea, covers 240 km^2 and has 580,097 inhabitants (2017) with an average population density of 2,417 inhabitants /km^2. The GDP in 2012 amounted to 20,529 €/cap. In 2017 a total of 3,533 tonnes of WEEE were collected, i.e. 6.1 kg / cap. The non-retail bring points receive 706 tonnes of WEEE (1.2 kg/cap), while the civic amenity sites (CAS) receive 2,825 tonnes (4.9 kg/cap).

With the launch of the WEEENMODELS project, the WEEE collection system in Genoa has been completely revised. AMIU created 47 new mobile collection points for small WEEE and 4 “ecological islands”, i.e. collection and recycling areas, distributed all over the territory, where citizens can bring their WEEE. The mobile collection system operates daily in different parts of the city. In practice the mobile collection system operates through a system of two equipped vans (ECOVAN+ and ECOCAR), which stop at different stations at scheduled times and locations, and where citizens can deposit their small WEEE and lamps. Small WEEE and IT can be brought to the ecological islands and to the ECOVAN+.

The WEEENMODELS project involved the testing of a mobile collection system of WEEE in 6 locations (all located to the western side of Genoa) for 5 months (September 2015 - February 2016) in order to understand if citizens would appreciate such collection system. Of the 6 collection stations, 2 have received very positive results, 2 were moderately used by citizens, and other 2 were almost not used. In total 1,172 kg of small WEEE were collected, out of which 377 kg could be reused.

The retailers who joined the WEEENMODELS project have a free platform, a container for collecting small WEEE, which is provided by AMIU, a low-cost collection service and the possibility to take WEEE to the AMIU Collection Centre, renovated for that purpose.

The communication campaign, carried out by AMIU, has increased awareness about the separate collection of WEEE. Workshops and laboratories were organized for young participants to increase their knowledge on the concept of circular economy.

1.6.2.4 Cyclad

The Cyclad Mixed Syndicate ensures the collection, treatment and recovery of waste produced by households in the region of the north-east of Charente-Maritime, France. It also organizes awareness campaigns for sorting and reducing waste. The syndicate's formation shows the political will of a rural area to make use of synergies for an efficient waste management system in a sparsely populated area. The average GDP in Charente-Maritime was 20,919 €/cap in 2005, being below the national average of 27,811 €/cap.

For waste collection, treatment and final land disposal, Cyclad provides services to 6 "intercommunalities", namely to the Aunis Atlantique, Aunis Sud, Vals de Saintonge, and Coeur de Saintonge, Gémozac and Saintonge Viticole, comprising 188 communes with 148,659 habitants covering an area of 2,704 km^2 (55 inhabitants / km^2). Further, they provide waste treatment services, but no collection, to Ile de Ré and Agglomeration of Saintes.

The recycling of WEEE is financed by the Eco-participation fee paid with each purchase of new equipment. More and more communities are offering this line to their waste treatment centres to facilitate sorting and promote recycling. This is the case for Cyclad, offering the collection in partnership with the PRO Eco-systèmes. Together they collect about 90% of the local WEEE. Lamps and batteries are collected separately by CorePile and Recyclum. At the big civic amenity sites (CAS), there are normally two containers for small WEEE & IT, and two for large WEEE. These containers are shared with Eco-systèmes and once they are full, Cyclad contacts Eco-systèmes to pick it up and transport it to the recycling facilities.

Cyclad also cooperates with a number of retailers. When the retailers' storage space is full, they call Eco-systèmes to pick up the WEEE. In addition, supermarkets provide drop off points for lamps, batteries and mobile phones. There are 5 social economy shops in theterritory, where people can drop off WEEE and buy second hand upcycled/recycled WEEE objects, i.e. the Emmaüs and Envie networks.

The biggest problem related to WEEE collection in the past was theft. In 2011 France introduced a legal ban on cash transaction for metals, to avoid WEEE leakage at borders and to include scrap dealers in the system and avoid WEEE non-compliant treatment. In order to protect metals, WEEE and batteries Cyclad bought containers (20ft) with special locks. In addition, they introduced video surveillance at all sites. They also painted the containers that are shared with Eco-systèmes in orange to make them easier to recognize. Further they have a special contract with the police, who regularly check the site to make sure that the employees are safe. Thanks to these measures the stealing decreased significantly and the WEEE flow is better under control. Further measures that increased the collected WEEE quantities include awareness raising campaigns to mobilize small WEEE that people keep at home in their drawers. Since there was a hoax in France that all WEEE is going to India, some campaigns have been launched to inform the general public on where the WEEE goes.

1.6.2.5 Vienna

Vienna, being the capital of Austria, covers 415 km^2 and has 1.87 million inhabitants (2017) with an average population density of 4,502 inhabitants /km^2. 40% of the population lives in multi-family houses, 60% in (semi)detached houses. The average household size is 2.06 persons. The GDP in 2017 amounted to 47,700 €/cap.

In Austria, around 80,000 tonnes of WEEE are collected every year; the ARA service group (specifically, the ERA compliance service) accounts for 40% of this amount. Every Austrian resident collects around 9.5 kg of WEEE per year. Consumers and businesses can drop off WEEE and used batteries at around 2,100 collection points across the country. In addition, people can also return WEEE to retailers/distributors when they purchase a new, equivalent device which fulfils the same functions as the old one, provided that the shop’s sales area is greater than or equal to 150 m^2. Batteries can always be returned to vendors free of charge without a need of purchase. In Vienna, there are 16 recycling centers (Mistplätze). The Austrian coordination body is called “Elektroaltgeräte- Koordinierungsstelle”.

Measures to improve the cost efficiency ratio include: public relation schemes, restrictions to informal-collection, reduction of expenses for logistics costs, increase revenue in marketing, improved collection pickup coordination with partners/recyclers. 3 WEEE categories are collected in containers: 30m^3 (small WEEE); lattice boxes (IT-monitors / display devices); 240l bins (gas-discharge lamps; w/ 120l bag, if broken).

1.6.3 Construction and demolition waste case studies

1.6.3.1 Odense

Odense is the 3rd largest city in Denmark with a population of 204,200 (Statbank Denmark, 2019). Odense is the commercial hub of Funen, and has a notable shopping district with a diversity of stores. Several major industries are located in the city including the Albani Brewery and GASA, Denmark's major dealer in vegetables, fruits and flowers. Odense has 8 recycling stations (CAS), with over 40 containers for collecting different waste materials. The vast majority of containers will be found at all the recycling stations in Odense. However, the smallest ones do not have space for all 40 containers. The CDW materials that are collected separately at the recycling stations include:

- Window glass with frames
- Window glass without frames
- Double glazing with Polychlorinated biphenyl (PCB)
- Asbestos and Ethernite
- Roofing board
- Gypsum
- Concrete and Bricks
- Mineral wool
- White toilets and washbasins
- Building waste with PCB
- Bricks only

Odense is a good example of a municipality involved in innovative CDW management schemes, leading the way in the reuse of old bricks which are being refurbished in Odense Renovation A/S's recycling centres. Previously, when bricks were delivered to Odense Renovation A/S, they were crushed and reused in construction projects, just like concrete and slate, but discarded bricks now have their own dedicated containers at the recycling centres (Gamble Mursten, 2019). When a container is full, it is driven to the Gamle Mursten factory in Svendborg on Funen, where they are cleaned and sorted before being stacked on pallets ready for reuse in new constructions. Odense also aims to collect both waste mineral wool insulation and waste ceramic sanitary ware separately in order to repurpose this material.

1.6.3.2 Reimerswaal

Reimerswaal is a municipality in the province of Zeeland in the south-western Netherlands on Zuid-Beveland, named after the lost city. The municipality had a population of 22,432 in 2017, and has a surface area of 242 km^2 of which 140 km^2 is water. The municipality of Reimerswaal was established in 1970, from the aggregation of the municipalities Krabbendijke, Kruiningen, Rilland-Bath, Waarde, and Yerseke.

The municipality is responsible for the collection and management of household waste and has this outsourced to private scheme The Zeeuwse Reinigingsdienst (ZRD). ZRD does the collection of all household waste (residual, organic, plastics and beverage cartons) as well as the management of all the CAS in Zeeland, where all CDW materials are collected.

2 Methodology

2.1Goal and scope

2.1.1 Goal

The goal of the LCA methodology presented in this report is to analyse holistically the material flows and environmental impacts associated with the processes involved in and affected by WCS in 12 different case studies in Europe, including the production, collection, sorting, recycling and disposal of material. The 12 case studies include: 5 PPW collection systems, 5 WEEE collection systems and 2 CDW collection systems (as described in section 1.6). The LCAs performed here provide insight into the environmental performance of WCS and the influential parameters during collection and sorting that effect both downstream treatment as well as upstream substitution of primary materials via recycling.

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 an alternative when 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 general scope of the LCA is to assess the waste management choices and the environmental implications of different waste streams, where well performing WCS are employed for those waste streams in Europe. In order to capture not only the potential environmental impacts generated by the WCS themselves, but also the consequences of the quality and quantity of collected wastes for resource recovery and substitution of primary production inputs, a broad system-perspective needs to be adopted. Therefore, the following life cycle stages are covered:

- 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 production stage includes the resource inputs and outputs required to produce the specific materials which flow through each waste stream, but does not include any additional assembly. This is because the assembly stage is not affected by decisions at the WCS, but by decisions at the product design stage. Likewise, 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. Some deviations to this general approach were necessary due to the nature of the different wastes and data availability. Therefore, the specific scopes are described in the following.

2.1.2.1 Paper and packaging waste

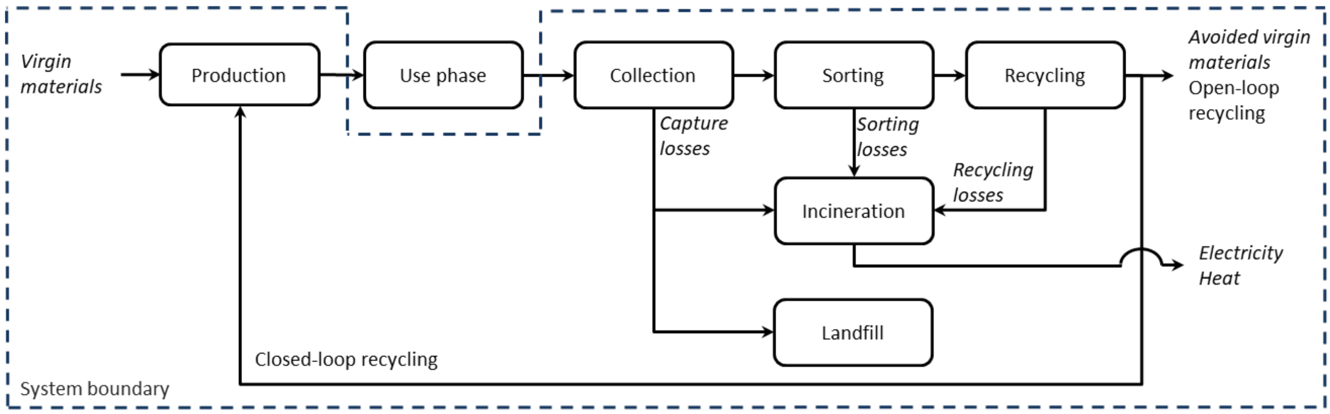

Figure 5: Flow diagram representing the life cycle phases of the PPW covered by the methodology.

The scope of the LCA of the PPW case studies is to assess the environmental impacts of each PPW material associated with each municipality, i.e. paper (non-packaging and packaging), plastic, metal, composite material and glass. The environmental impacts associated with the production of each material, the collection and sorting of the waste generated, and the fate of each material are all considered within the system boundary of the model (Figure 5). The packaging 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 WCS includes all collected waste that is separated from residual waste by the inhabitants and does not assume any mechanical recovery of the packaging materials from the residual waste after collection.

2.1.2.2 Waste electrical and electronic equipment

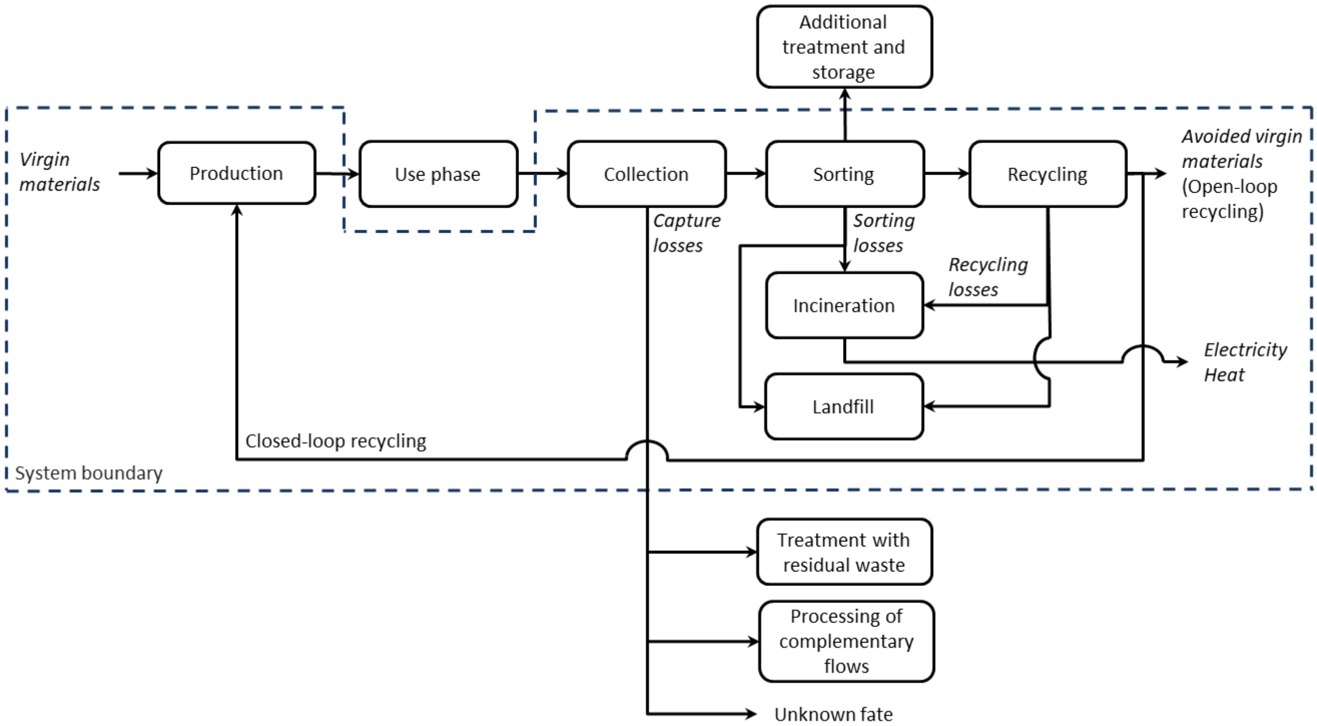

Figure 6: Flow diagram representing the life cycle phases of the WEEE covered by the methodology.

The scope of the LCA of the WEEE case studies is to assess the environmental impacts of each material associated with three WEEE categories (small WEEE, IT and lamps) in each municipality. The environmental impacts associated with the production of each material, the collection and sorting of the waste generated, and the fate of each material are considered (Figure 6). As previously mentioned, the assembly stage is not considered; like the use phase, the assembly of the electrical and electronic equipment can be assumed not to change as a result of decisions at the WCS. Furthermore, it would be extremely difficult to accurately capture the complexities of assembling every type of equipment in each category within the model. The constituent material is produced from both virgin and recycled material, the proportions of which are dependent upon the capture rate of each category (and its material composition) at the collection stage, the material losses at the sorting and the recycling stages, and the demand for each recycled material in the production of electrical and electronic equipment. Materials that are not collected via a designated WEEE WCS are counted as capture losses; because the treatment of these materials is unclear, these materials were not considered in the LCA. Material is sorted both manually and mechanically at the sorting stage. Material is shredded then sent for further processing, ultimately being sent for recycling, to landfill, incineration with energy recovery or further treatment, as is assumed for hazardous materials.

In addition for WEEE, the results of "good practice actions" performed by the PRO in the case study (e.g. transport optimization, pickup frequency increase, collection point density increase, awareness campaigns, etc.) are analysed. We call this a "delta analysis" as the analysis of the performance of the WEEE collection system was done for two points in time, i.e. before and after improvement actions. The effects of these changes on the environmental impacts are presented in this report.

2.1.2.3 Construction and demolition waste

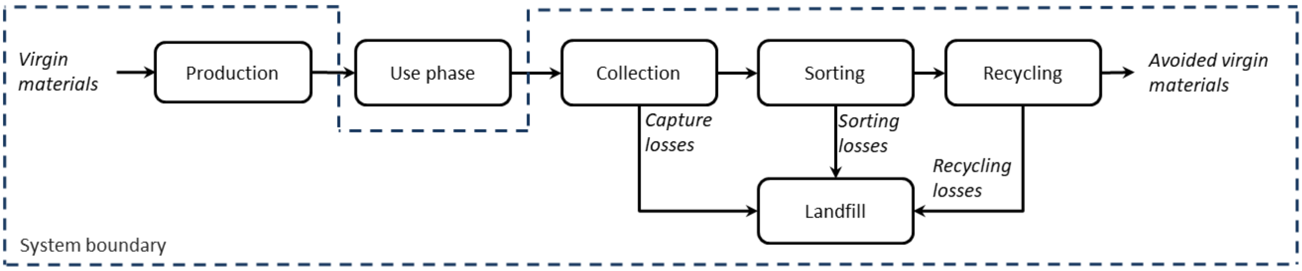

Figure 7: Flow diagram representing the life cycle phases of the CDW covered by the methodology.

The scope of the LCA of the CDW case studies is to assess the environmental impacts associated with four CDW materials, these are: bricks, insulation, sanitary ceramics and gypsum. The environmental impacts associated with the production, collection and sorting of the waste generated, and the fate of each material are all considered. Unlike in the PPW and WEEE models, data were not available on the amount of each material produced annually and therefore the demand for the recycled material could not be considered. As a result, we were not able to distinguish closed-loop and open-loop recycling, but just the potentially avoided impacts from replacing virgin materials with the recycled materials after considering the losses during collection, sorting, and recycling (Figure 7).

2.2General material flow model

The LCA of each case study followed the methodology described comprehensively in D3.1 of the COLLECTORS project. This core of this methodology is outlined in this section.

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 1). As discussed in section 2.1.2.3, the LCA of the CDW does not consider the production of the material, only the avoided impacts of recycling the CDW. Hence equations 1 and 2 are not applied to CDW in this report.

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

Equation 1

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 (steady-state assumption; Equation 2).

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

Equation 2

The proportion of material produced from primary production and from 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 3). 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, 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 to recycling inefficiencies ($l_{recycling}$). Considering all these losses together is important for determining how much material is ultimately recycled (Equation 3).

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

Equation 3

Recycled materials do not completely replace the virgin materials in a product, 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.). Another factor that determines the amount of virgin material that can be replaced via closed-loop recycling is the economic competitiveness of recycled material within the free market (Gala, et al., 2015). The proportion of recycled material that can substitute virgin material within a product is defined by the substitution rate ($r_{substitution}$) of each material (Appendix Table B-2). In other words, the maximum share of recycled materials that can technically be included in new products.

The demand for each material is determined based on steady-state analysis (Equation 2), 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 4).

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

Equation 4

Within the model, the amount of material recycled in a closed-loop is, therefore, limited by the maximum demand for recycled material, $F_{substitution,\ max}$, (Equation 5).

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

Equation 5

If the quantity of recycled material, $F_{recycled\ material}$, is higher than the maximum demand, $F_{substitution,\ max}$, only the as much as the maximum demand goes to closed-loop recycling, while the rest goes to open-loop recycling (Equation 6).

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

Equation 6

For the calculation of all material flows, we consider the quality of materials, for example to ensure that materials going to closed-loop recycling are of sufficient quality to replace virgin materials in their original application. For open-loop recycling, i.e. where the amount of a recycled material exceeds the demand for it from its original market, or where the recycled material is not of sufficient quality to be used in the original market, recycled materials are assumed to displace virgin materials for the use in other applications. 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, recycled material entering the open-loop recycling is assumed to avoid the production of the same material, of equal quality, from virgin materials.

The environmental benefits associated with the use of secondary materials (in closed and open-loop recycling) can be calculated as the difference of producing virgin materials and the collection, sorting, and recycling of the secondary materials. In some cases, entirely different raw materials may be replaced by a recycled material (Suter, et al., 2017). Thus, the impacts associated with closed-loop recycling must be regarded as indicative of the potential avoided impacts associated with the collected material only. In some cases, a target market for open-loop recycling is identified (e.g. aluminium from composite material enters the cement industry and glass from WEEE enters the ceramics industry), in these cases the avoided impacts associated with the conventional material that is substituted is calculated.

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 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). Incinerating this material releases energy that can be recovered. The entirety of material that is lost during treatment (i.e. the sorting and recycling losses) is assumed to be sent for incineration with energy recovery. The energy captured during the incineration process can displace the equivalent energy production based on inputs in corresponding national averages.

2.3Life Cycle Assessment modelling of waste streams

2.3.1 Paper and packaging waste

2.3.1.1 Primary production

The LCA performed builds upon unit processes for each PPW material considered that are available in the ecoinvent database (Wernet, et al., 2016), which are specific to European production where possible (see Appendix Table E-1 for a list of these processes and adaptations made). The environmental impacts associated with the primary production of each material considered in this project, i.e. when materials are produced from virgin materials only, are presented in Appendix Table B-1.

2.3.1.1.1 Paper

Paper represents 49% of the total PPW produced in Europe (Eurostat, 2016) including the carton board (2.3%) recovered from composite material. This is made up of newsprint and other non-packaging paper, graphic paper, cardboard and other packaging paper (Pivnenko, et al., 2016; FAO, 2018). The primary production of paper includes wood handling, mechanical pulping, paper production, on-site energy use and internal waste water treatment.

2.3.1.1.2 Plastic

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.

2.3.1.1.3 Glass

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. The primary production of glass includes material and energy inputs, water consumption, emissions to air and water, waste generation 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 automated 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 is used as a fluxing agent 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 the form of limestone ($CaCO_3$ that decomposes to CaO), dolomite, and feldspar are used to improve the hardness and chemical resistance of glass.

2.3.1.1.4 Metal

Metal represents 6% of the PPW produced in Europe by mass, of which 75% is aluminium and 25% is 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. 1.5 MJ of heat is required per kg of aluminium and supplied almost entirely from natural gas. 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, melting of recovered aluminium 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 melted 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.

2.3.1.1.5 Composite material

Packaging made out of composite material represents only a small proportion of PPW generated in Europe; 3% of the PPW by mass (Eurostat, 2016). 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.

2.3.1.2 Substitution and substitutability of primary materials

The substitution rates (i.e. the maximum share of the recycled material that can technically be included in new products) of each material considered in this project are presented in the Appendix Table B-2.

2.3.1.2.1 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).

2.3.1.2.2 Plastic

The quality losses of the recycled polymers in the closed-loop recycling 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.

2.3.1.2.3 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 61%, 84% and 55% on average for white, green and brown glass respectively.

2.3.1.2.4 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 rates of aluminium and steel packaging is presumed to be 75% and 50% respectively (Gala, et al., 2015).

2.3.1.3 Collection and sorting activities

The transport associated with each material is based on data (when provided) from each of the municipalities included as case studies. The energy and resource inputs and outputs at the sorting stage are based on average European requirements for each material. The transport from the sorting facilities to recycling facilities is based on European averages for each material and is included as part of the closed-loop recycling impacts and not the collection and sorting impacts. This is because municipalities are not responsible for the transport of this waste. Key data for each municipality (e.g. absolute waste quantities and capture rates) are reported as part of the results in section 3.1.1.

2.3.1.3.1 Paper

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). Four grades are considered in this study and 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) (see Appendix Table B-3).

2.3.1.3.2 Plastic

Although some recovered plastic is separated by curb side sorting and the use of separate bring points, sorting and separation of plastics most commonly takes place at sorting facilities. Sorting operations range from manual sorting of items on a conveyor to highly automated systems using magnets, air classifiers, optical sorters, and other technologies to sort and separate mixed incoming materials. 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. Averages datasets for Europe are applied to the sorting process of each plastic. Due to a lack of data on the sorting of PP and PS, the process “market for waste polyethylene, for recycling, sorted” is adapted to quantify these impacts. The plastics are heated and shredded so that they become pellets which can be used in manufacturing.

2.3.1.3.3 Glass

Glass is most often sorted into different colours at the collection point. Further sorting takes place after the glass is crushed into cullet, ready to be sent for recycling. The “market for waste glass” ecoinvent process is used to calculate the impacts associated with sorting.

2.3.1.3.4 Metal

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. The metal that can be potentially extracted from slags of incinerators are excluded.

2.3.1.4 Closed-loop recycling

The environmental impacts of producing each material via closed-loop recycling, i.e. recycled material is incorporated at the substitution rate during the production of the material, are shown in the Appendix Table B-2.

2.3.1.4.1 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).

2.3.1.4.2 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. As there is no process for recycled polypropylene, this process has been adapted for closed-loop recycling based on “waste polyethylene, for recycling, sorted”, replacing the virgin material inputs by 75%.

2.3.1.4.3 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 melting 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.

2.3.1.4.4 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 re-enters the production at the metal packaging in the holding furnace where it is melted and combined with virgin materials. The aluminium recovered from composite material is used as a bauxite substitute in cement (Pretz & Pikhard, 2010).

2.3.1.5 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.

2.3.1.6 Disposal

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). 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 is assumed to displace (avoid) the equivalent amount of energy of the national average energy mix, which is available at a country level for electricity and at the EU level for heat from the ecoinvent database (associated impacts are reported in Appendix Table A-1). The environmental impacts of incinerating each material are added to the total impacts of the system, whereas the impacts associated with the avoided energy production based on European averages are subtracted from the total impacts.

2.3.2 Waste Electrical and Electronic Equipment

2.3.2.1 Primary production

The constituent materials of all three categories (small WEEE, IT and lamps) are broadly: plastic, metal and glass (details are provided in Appendix Table C-1). The LCA is performed using datasets available in the ecoinvent database specific to European production (see Appendix Table E-1 for a list of these processes and adaptations made). The environmental impacts associated with the primary production of each material considered in this project, i.e. when materials are produced from virgin materials only, are presented in the Appendix Table C-2.

2.3.2.1.1 Plastic

The main types of plastic in WEEE are acrylonitrile butadiene styrene (ABS), polyamide (PA), polybutylene terephthalate (PBT), polycarbonate (PC), PP (see section 2.3.1.1.2), high impact polystyrene (HIPS), PE, Polyvinyl chloride (PVC) and bromated plastic. As with the plastic packaging, the data on the production of each type of plastic 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 ready to be incorporated into electrical or electronic equipment.

PBT is produced by emulsion polymerization out of its three monomers. PC is produced by interfacial polycondesation out of phosgene and bisphenol A. HIPS is produced via the polymerization of ethylene and benzene by free radical processes. PVC is produced through emulsion polymerization of vinylchloride. Bromated plastic is assumed to be decabromodiphenylether, which is produced via a batch reaction of bromine and diphenyl ether with the aid of a catalyst (Pakalin, et al., 2007).

2.3.2.1.2 Metal

The main metals contained in electrical and electronic equipment are iron, aluminium and copper. WEEE contains small quantities of precious metals: gold (Au), silver (Ag) and palladium (Pd). WEEE also contains Indium and hazardous materials such as lead, cadmium and mercury. The environmental impacts of primary production are based on aggregated data for all processes from raw material extraction and processing of the metals until they are ready to be incorporated into electrical and electronic equipment.

The primary production of aluminium is described in section 2.3.1.1.4. Iron is produced using a blast furnace process requiring, amongst other inputs, 9.7 MJ per kg produced from coke. In primary copper production, ore is pre-treated, reduced and refined according to the European mix of process alternatives including reverberatory furnace and flash smelting furnaces, followed by melting, alloying, and casting. This requires, amongst other inputs, 0.55 kWh of electricity and 7.9 MJ of heat per kg of copper. Indium is produced using residues from hydrometallurgical zinc extraction. Crude indium is formed by the precipitation of a sponge, from this indium cathodes are cast followed by electro-refining, then by vacuum-refining. The extraction, concentration and refinement of precious metals are considered specific to the gold, silver and palladium industry. For mercury production impacts were approximated with data from lime mining, crushing and milling plus estimation of the additional furnace operation step, based on information in ecoinvent.

2.3.2.1.3 Glass

The included production steps in the production of glass are: raw material extraction preparation and sorting of cullet, melting, forming of flat or funnel shaped glass parts (depending on the final use, i.e. liquid crystal display, cathode-ray tube etc.), cooling down etc. until the glass parts are ready for the next process step in the assembly of electrical and electronic equipment. As with all the other materials, direct emissions to air, waste water, and other waste outputs are included in the model. It is assumed that the inputs to the production of this funnel glass include, amongst others, 0.25 kWh of electricity, 9.7 MJ of heat and 0.08 kg of lead per kg, whereas the production of glass for liquid crystal displays required 2.8 kWh of electricity and 21 MJ of heat per kg.

2.3.2.2 Substitution and substitutability of primary materials

The substitution rates of each material considered in this project are presented in the Appendix Table C-3. Only aluminium, iron, copper and the precious metals were considered to substitute materials in the production electrical and electronic equipment. Other recyclable material is assumed to enter open-loop recycling.

2.3.2.3 Collection and sorting activities

The European Commission sets out a number of provisions in its WEEE Directive which all member states and all producers and distributors operating in the countries must comply with. Such regulations include setting up take-back schemes, ensuring private consumers can hand in their WEEE free of charge; and collecting WEEE separately from other waste streams. In practice, WEEE can be either collected directly from or by private companies and taken to the appropriate sorting facilities (particularly the case for larger appliances), collected from designated bring points (e.g. lamps, batteries etc.), or directly disposed of in CAS or other services by the customer. From the point of collection, each WEEE category is transported to the appropriate sorting facility. The transport distance and method are specific to each municipality. Upon arrival at the sorting facility the WEEE is shredded; hazardous components and substances must be removed for additional treatment and storage in some cases (e.g. mercury), whilst other materials are either processed for recycling or incinerated with energy capture. Key data for each municipality (e.g. absolute waste quantities and capture rates) are reported as part of the results in section 3.2.1.

In addition to the recycling process described above, some WEEE may be collected with the intention of reuse. In this situation, the production of the equivalent electrical and electronic equipment might simply be avoided. Whilst reuse is not considered in the base model described here (see section 2.1.2.2), the avoided impacts associated with the production of the materials can be calculated easily. These avoided impacts can be subtracted from the total impact associated with the WEEE category when calculating its net environmental impacts. The avoided impacts associated with the assembly of the electrical and electronic equipment is not included within the assessment, as to be consistent with the original production of the devices within the model. Results for reuse are presented in section 3.2.3.

2.3.2.4 Closed-loop recycling

It is assumed that the amount of material that can be recycled in a closed loop is used in the production of the electrical and electronic equipment. As with PPW, and to be consistent in the modelling approach, the demand for these recycled materials for electrical and electronic equipment is considered based on market demand and material quality reductions (i.e. if the amount of recycled materials is higher than the demand within closed-loop recycling, open-loop recycling is assumed).

The recycling of copper form WEEE ends with the electrolysis of copper anodes before it is combined with virgin material. The dataset includes the collection and handling of the copper scrap, the smelting of scrap in the blast furnace, conversion in the converter, the refining of converted copper in an anode furnace, and the hydrometallurgical treatment of scrap. Anode slime treatment by pressure leaching and the use of a top blown rotary converter, followed by electrolysis results in the recovery of precious materials. Here a recovery rate of 26% of the precious material available in collected WEEE is assumed (Bigum, et al., 2012; Chancerel, et al., 2009).

Results for the “delta analysis”, i.e. increased benefits of closed-loop recycling through improvements of the collection system (e.g. increased capture rates) between two points in time are described in section 3.2.2.2 and shown as a reduction in the environmental impacts associated with production.

2.3.2.5 Open-loop recycling

Current sorting devices are not capable of reaching the segregation levels necessary for the removal of contaminants in recovered plastic. Currently only ABS and HIPS are mechanically recycled from waste streams on an industrial scale (Wagner, et al., 2018; Biganzoli, et al., 2015). This plastic enters open-loop recycling. The other plastics can be incinerated with energy recovery. In addition to these plastics, recovered indium and cadmium are assumed to enter open-loop recycling. All recovered glass is assumed to be recycled in an open-loop, replacing frit in the ceramics industry (Biganzoli, et al., 2015).

For WEEE, the avoided environmental impacts associated with open-loop recycling and energy recovery from incineration are combined; this is henceforth referred to as substitution benefits.

2.3.2.6 Disposal

The sorted material that could not be recycled, but could be incinerated, such as all plastics from WEEE apart from ABS, HIPS and bromated plastics, were assumed to be incinerated with energy recovery. Non-hazardous material that is not able to be recycled or incinerated is sent to land fill.

The presence of hazardous substances has been limited or restricted in electrical and electronic equipment (The European Parliament and the Council of the European Union, 2005). However, WEEE that is now being processed still contains these additives, which are affecting processing in several different ways (Tansel, 2017; Maris, et al., 2015). Hazardous materials, such as mercury, receive additional treatment and storage, but due to the lack of data, these processes have not been considered.

2.3.3 Construction and Demolition Waste

2.3.3.1 Primary production

As discussed in section 2.1.2.3, the production of the CDW materials are considered for bricks, insulation, sanitary ceramic ware and gypsum. The LCA is performed using datasets available in ecoinvent specific to European production (see Appendix Table E-1 for a list of these processes and adaptations made).

2.3.3.1.1 Bricks

This dataset used to model the primary production of bricks in Denmark includes the first grinding process, wet process (second grinding and mixing), forming (an extruding moulding method) and cutting, drying, firing, loading, packing and ends with the storage of the produced and packed brick at the factory. Amongst other inputs, 1.35 kg of clay, 0.03 MJ of diesel and 0.04 kWh of electricity are required per kg of brick production.

2.3.3.1.2 Insulation

Mineral wool is used as the reference for insulation material. The density of the mineral wool used as the basis for the study is 40 kg/m^3, taken from the ecoinvent process where 80% of the material mass is derived from glass cullet. The included processes are: melting, fibre forming & collecting, hardening & curing furnace, and internal processes, requiring 2.3 kWh of electricity and 0.05 MJ of diesel per kg amongst other inputs. The extraction and transport of raw materials and the energy carrier for furnace are all included within the model.

2.3.3.1.3 Sanitary ceramic ware

Sanitary ceramics are made from ingredients such as clay, feldspar, kaolin, silica sand and others and are assumed to be produced in a gas fired kiln. The main processing steps involve milling, batching, forming, drying and sintering. During these processing steps 23 MJ of heat and 0.9 kWh of electricity are required per kilogram of oxidic sanitary ceramics.

2.3.3.1.4 Gypsum

To produce gypsum plasterboard, natural gypsum is crushed and heated, mixed with water and additives to form a slurry which is fed between continuous layers of paper fibres on a long board machine. As the board moves down the line, the calcium sulphate recrystallizes or rehydrates, reverting to its original rock state. The paper becomes chemically and mechanically bonded to the board, which is then cut to length and conveyed through dryers to remove any free moisture. Energy consumption is extrapolated in the model from the production of solid gypsum board.

2.3.3.2 Substitution and substitutability of primary materials

The recycled CDW material (i.e. after collection and sorting) is assumed to be able to substitute virgin material at a 1:1 ratio. Thus, every recycled brick could replace the production of one brick from virgin materials. Likewise, the recovered mineral wool and gypsum are assumed to replace the mineral wool and gypsum in the production of new insulation and plasterboard respectively.

In contrast, sanitary ceramic ware (toilets, sink basins etc.) are not recycled into new sanitary ceramic ware (i.e. not recycled in a closed-loop). Instead, waste sanitary ceramic ware was reported to be used in the production of concrete as a replacement for aggregates (i.e. sand and gravel). Hence, the avoided impacts associated with collected waste sanitary ceramic ware are associated with the avoided input of sand and gravel in the production of concrete. Sanitary ceramic waste can potentially replace up to 50% of the fine aggregate and 25% of the course aggregate in concrete (Guerra, et al., 2009; Medina, et al., 2012). Thus, based on the composition of concrete, it is assumed that 53% of the sanitary ceramic waste that is collected is crushed into fine grains and substitutes sand, the remainder of the ceramic material is crushed into finer grains and substitutes gravel in concrete production.

2.3.3.3 Collection and sorting activities

2.3.3.3.1 Odense - Bricks, insulation and sanitary ceramics

In Odense, 1300 tonnes of waste bricks was generated in 2018, of which 62% were captured (806 tonnes). Of that amount, 65% were in good enough condition to be reused in new buildings and 35% were in somewhat damaged condition and thus collected for recycling. The reused bricks are transported over a distance of 225 km in 33 tonne trucks (Møller, et al., 2013). The damaged bricks are processed into road filling material and are transported over a distance of 50 km in 33 tonne trucks.

200 tonnes of insulation were collected in Odense in 2018, of which 98% was ultimately recycled. This is transported over a distance of 6 km from the CAS in Odense to the company NORECO.

140 tonnes of sanitary ceramics were collected at the CAS in Odense in 2018 and transported over a distance of 6 km to the company HJ Hanson.

2.3.3.3.2 Reimerswaal - Gypsum

At the CAS in Reimerswaal, operated by ZRD, the Gypsum is separately collected (capture rate of 81%) before being transported for further recycling; processed into gypsum powder and subsequently used to make new plaster products. 102 tonnes of Gypsum were collected in 2018. Only clean gypsum waste is collected, free from tiles and wood. The material is transported over a distance of 60 km to Antwerp, Belgium.

2.3.3.4 Recycling

2.3.3.4.1 Bricks

The bricks arrive at the reprocessing premises where they are stored. The material is then handled with one diesel powered front loader. An electric powered outdoor conveyor belt system, equipped with grates and sieves, then sorts the bricks from other residues such as mortar and wood. The reusable bricks are then sorted from the broken bricks by hand, before being stacked by a propane-powered forklift truck (Møller, et al., 2013). The broken waste bricks are assumed to be crushed and used as a gravel substitute in road filling. Thus, avoiding the whole manufacturing process (crushing, transport, etc.) and infrastructure for providing gravel.

2.3.3.4.2 Insulation

After recovery, the mineral wool fibres are washed. The washing process consumes 5.6 kg of water and 0.001 kg of soda per 1 kg of mineral wool fibres (Gao, et al., 2001; Väntsi & Kärki, 2015). The washed mineral wool fibres are then dried. The drying process consumes 2.3 MJ of thermal energy per 1 kg of mineral wool fibres, the impacts of which are calculated according to the EU27 average data. A further 4.4 MJ of electricity is needed in the recycling process, the impacts of which are based on the Danish market mix for electricity production (Gao, et al., 2001; Väntsi & Kärki, 2015). The washed and dried mineral wool fibres are transported by truck to the composite extrusion plant.

2.3.3.4.3 Gypsum

Of the total weight of collected gypsum, 81% is assumed to be recoverable at the sorting and recycling stages. Recovered gypsum is crushed, and then the paper and gypsum are separated (Suárez, et al., 2016). A value for the consumption of 0.04 MJ of diesel in the recycling plant, which is used in the crushing and separation of gypsum and paper, is obtained from ecoinvent.

2.3.3.5 Disposal

Disposal included the energy for dismantling, particulate matter emissions from dismantling and handling, transport to dismantling facilities, final disposal of waste material. Mineral wool and bricks that are not captured are assumed to be disposed of in inert landfills. Gypsum that is not collected is assumed to be disposed of in sanitary landfills. For each material, the LCA is modelled based on disposal process datasets found within ecoinvent. Any material that is disposed of in landfills is assumed to be transported 15 km.

2.4 Impact assessment

All materials covered in this report are at least partly produced from fossil resources and thus not only deplete these, but also contribute to GHG emissions and thereby climate change. Further, during production and waste management, emissions to the air, water, and soil may occur, e.g.

during incineration, wastewater treatment or landfilling. These emissions may lead to a broad range of environmental impacts, including ecotoxicity, eutrophication, and acidification. We therefore include six impact categories based on the expected types of impact on the environment from WCS as well as the considered up- and downstream processes (Skals, et al., 2007; Arena, et al., 2004; Lopes, et al., 2003): 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). We apply the ReCiPe impact assessment methodology to calculate the impact scores (Goedkoop, et al., 2008). Considering several impact categories simultaneously helps to identify trade-off situations and is the basis for identifying environmental burden-shifts.

2.5Sensitivity analysis

Sensitivity analyses are performed for key parameters that exert a strong influence on the environmental impact results for each impact category for each case study. For PPW, these parameters are: the material losses at the collection stage, the material losses at the sorting stage and the material losses during the recycling stage for each material. For WEEE, the material losses at the collection stage and sorting stages are adjusted. Recycling losses are not adjusted for WEEE due to data limitations. Sensitivity analysis for the material losses at the collection, sorting, and recycling stages are performed by increasing the capture rate, as well as sorting and recycling efficiencies, by each 10%. The changes in the total environmental impacts of the entire life cycle for each waste category and type, when important parameters are adjusted, are reported.

3 Results and discussion

3.1 Paper and packaging Waste

3.1.1 Material flows

3.1.1.1 Parma

The municipality of Parma (inhabitants and similar waste producers such as small commercial activities and public organisations) reported to have generated 17679 tonnes of paper, 7560 tonnes of plastic, 2394 tonnes of metal, 9807 tonnes of glass and 445 tonnes of composite material (Figure 8). Parma achieved a capture rate of 81%, 69%, 33% 93% and 36% for these materials respectively. 34% of the material that enters the residual waste is incinerated in Italy (Eurostat, 2019). Parma is currently meeting 2025 recycling targets of the European Union for paper, plastic and glass.

Material	Mass (kg)	Recycling rate
Paper	1.42E+07	80%
Plastic	4.01E+06	53%
Metal	7.90E+05	33%
Glass	7.30E+06	74%
Composite material	1.27E+05	28%

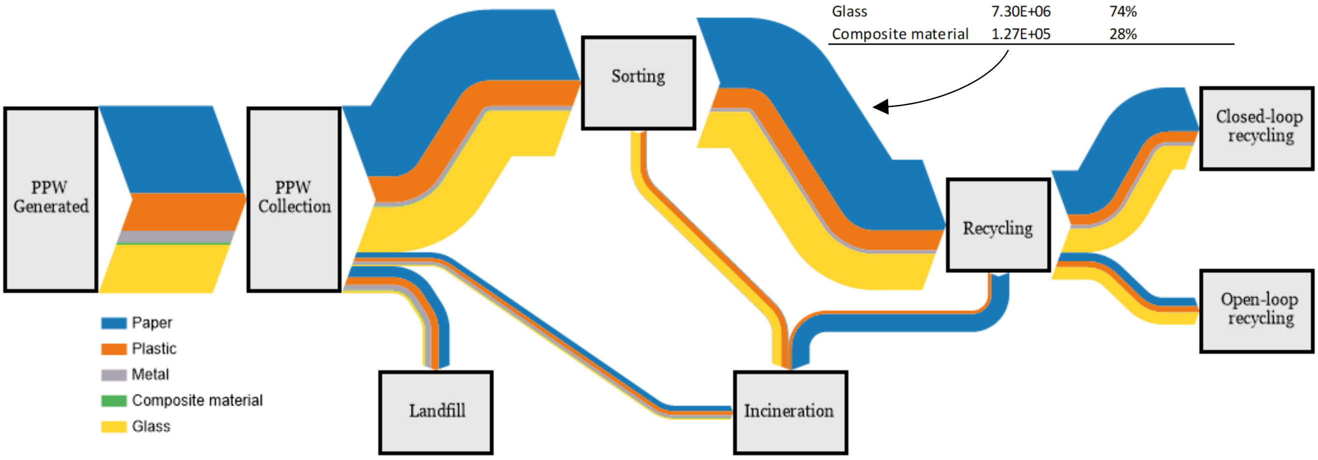

Figure 8: PPW material flows in the municipality of Parma

3.1.1.2 Tubbergen

The municipality of Tubbergen reported to have generated 1903 tonnes of paper, 449 tonnes of plastic, 41 tonnes of metal, 507 tonnes of glass and 76 tonnes of composite material (Figure 9). Tubbergen achieved a capture rate of 100%, 68%, 53%, 100% and 66% for these materials respectively. 81% of the material that enters the residual waste is incinerated in the Netherlands (Eurostat, 2019). Tubbergen is currently meeting the 2025 recycling targets of the European Union for paper, plastic and glass and non-ferrous metal. Tubbergen is currently already achieving the 2030 recycling targets for paper and glass.

Material	Mass (kg)	Recycling rate
Paper	1.88E+06	99%
Plastic	2.31E+05	51%
Metal	2.19E+04	53%
Glass	4.06E+05	80%
Composite material	3.94E+04	52%

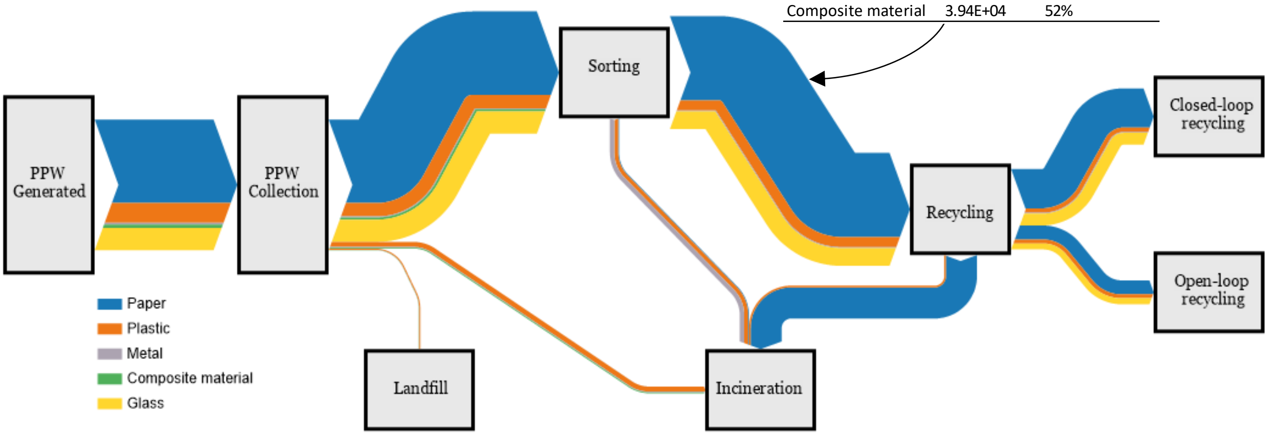

Figure 9: PPW material flows in the municipality of Tubbergen

3.1.1.3 Gent

The municipality of Gent reported to have generated 16304 tonnes of paper, 2056 tonnes of plastic, 1291 tonnes of metal, 8755 tonnes of glass and 483 tonnes of composite material (Figure 10). Gent achieved a capture rate of 85%, 69%, 82%, 93% and 48% for these materials respectively. 99% of the material that enters the residual waste is incinerated in Belgium (Eurostat, 2019). Gent is currently meeting both the 2025 and 2030 recycling targets of the European Union for paper, metal and glass.

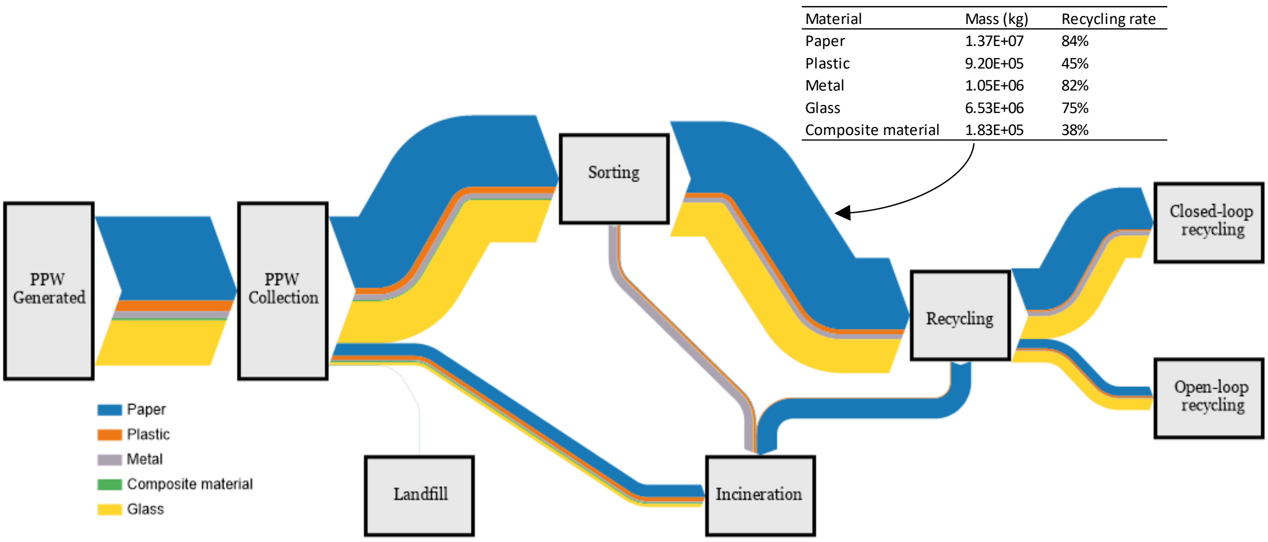

Figure 10: PPW material flows in the municipality of Gent

3.1.1.4 Berlin

The municipality of Berlin reported to have generated 169473 tonnes of paper, 45000 tonnes of plastic, 14400 tonnes of metal, 66830 tonnes of glass and 9000 tonnes of composite material (Figure 11). Berlin achieved a capture rate of 67%, 40%, 47%, 57% and 18% for these materials respectively. 90% of the material that enters the residual waste is incinerated in Germany (Eurostat, 2019). Berlin is currently not meeting the 2025 recycling targets of the European Union for any PPW material. The organisation of Berlin's waste collection is complicated due to historic reasons; collection and sorting are not completely aligned, for instance some areas collect brown and green glass together and for other areas these are collected separately. Berlin employs a PET bottle deposit scheme; such schemes make data collection more difficult (Lee, et al., 2017), thus it is likely that the collection of plastic is underestimated here.

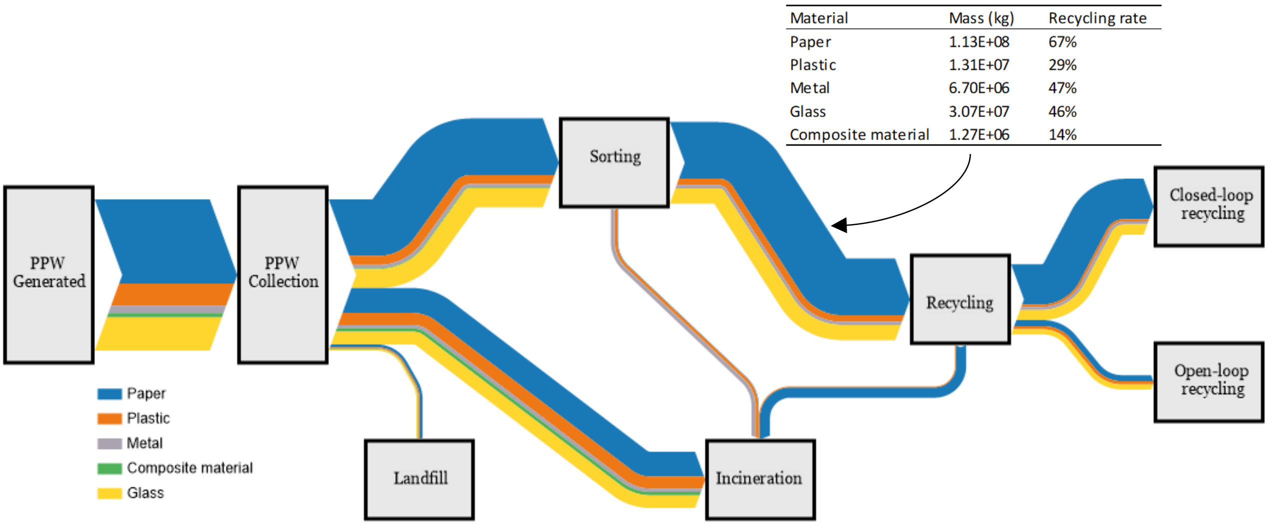

Figure 11: PPW material flows in the municipality of Berlin

3.1.1.5 Rennes

The municipality of Rennes reported to have generated 24200 tonnes of paper, 10350 tonnes of plastic, 3100 tonnes of metal, 19650 tonnes of glass and 1972 tonnes of composite material (Figure 12). Data were obtained from (Metropole Rennes, 2017). Rennes achieved a capture rate of 59%, 25%, 43%, 77% and 27% for these materials respectively. 28% of the material that enters the residual waste is incinerated in France (Eurostat, 2019). Rennes is currently not meeting the 2025 recycling targets of the European Union for any PPW material.

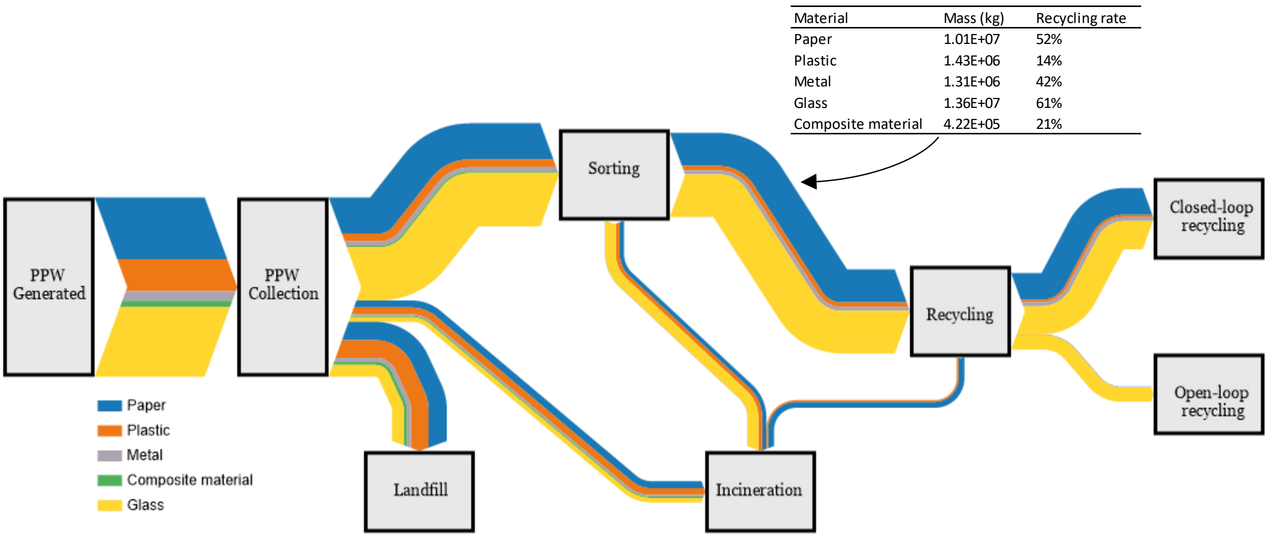

Figure 12: PPW material flows in the municipality of Rennes

3.1.2 Environmental impacts

The environmental impact values associated with the functional unit (1 kg[1] of waste generated for each material) for each impact category are similar between the case studies (Figure 13 to Figure 18, where "x" represents the net impact including substitution), although the impacts are often concentrated at different stages of the material life cycle for the different impact categories assessed. Metal has the largest GWP in Parma, Tubbergen, Berlin and Rennes, whereas plastic has the largest GWP in Gent. Plastic has the largest FDP in Tubbergen, Gent, Berlin and Rennes, whereas metal has the largest FDP in Parma. Metal has the largest associated FEP, MEP, TAP and METP per kg among the considered materials.

Gent is the only municipality to collect enough metal to meet the demand for metal via closed-loop recycling. Thus, some metal enters open-loop recycling. Tubbergen is the only municipality to collect sufficient glass to meet the demand of brown glass via closed-loop recycling. Some glass entered open-loop recycling in every case, due to it being of insufficient quality to enter closed-loop recycling.

Although increasing capture rates lead to an axiomatic increase in the impacts associated with the collection and sorting with each PPW material, the impacts associated with this life cycle stage are relatively small. The collection and sorting stage is also dependent upon the transport distances reported for each waste material. The environmental impacts associated with the collection and sorting of the PPW accounted for only a small portion of the overall impact for each impact category. For instance, the GWP associated with collection and sorting for each material ranged from 0.5% (for paper in Rennes) to 4.0% (for the plastic in Parma).

Berlin has the second highest incineration rate of case studies and the most avoided impacts associated with energy recovery (Figure 13). This is due to the fact Germany's conventional energy production is still relatively carbon intensive.

It is important to note that increased environmental impacts associated with closed-loop recycling of a material is directly related to decreased impacts from primary production. This is because

[1] The figures can easily be read as well as *impacts per ton of waste* by replacing the "kg" by "ton" on the vertical axis, e.g. "ton CO2-eq." instead of "kg CO2-eq."

production with closed-loop recycling replaces primary production. Closed-loop production often has lower impacts per kg of material then primary production (see Appendix Table B-1 and Appendix Table B-2). Therefore, municipalities with the highest impacts related to closed-loop recycling of a specific material have the lowest impacts associated with the primary production of that material. Closing the loop in a circular economy requires the primary production to be replaced as much as possible by production with closed-loop recycling. As is considered in section 2.2, replacing primary production entirely with closed-loop recycling will still require some raw material inputs with current recycling methods and quality requirements.

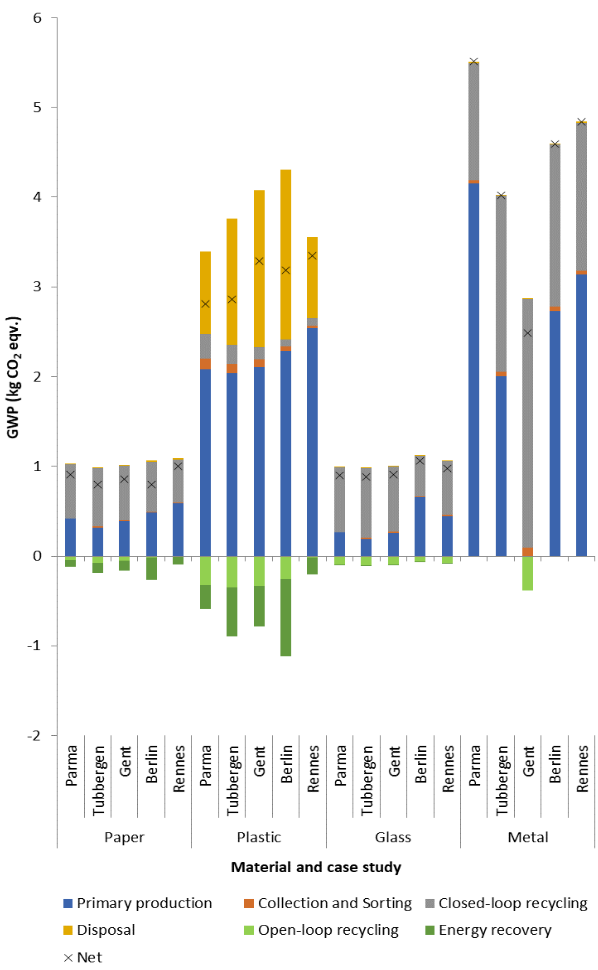

Figure 13: Global warming potential (GWP; kg CO_2-eq.) per kg of each PPW material generated.

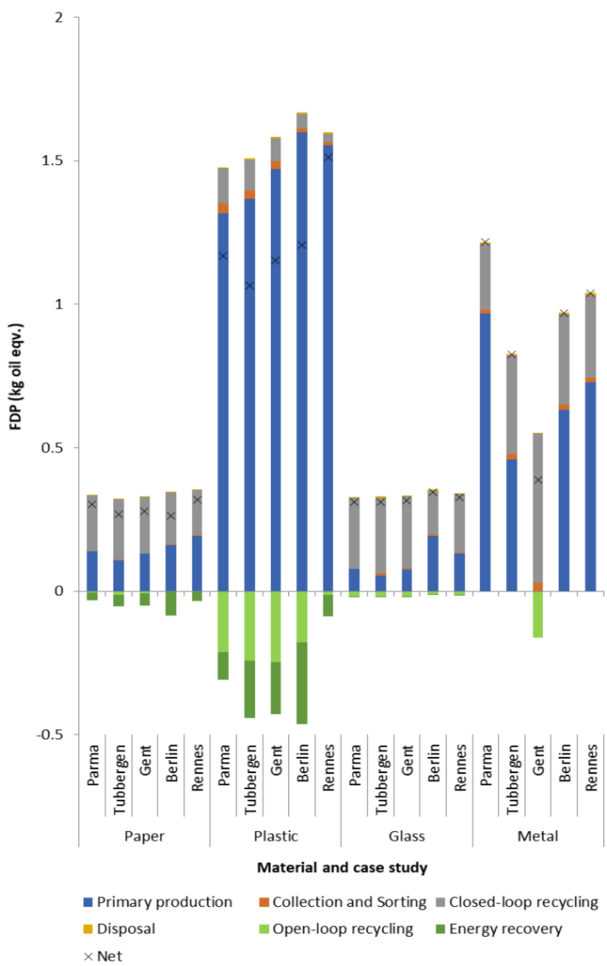

Figure 14: Fossil depletion potential (FDP), calculated as the equivalent energy based on the upper heating value of crude oil, (42 MJ per kg, in ground) per kg of each PPW material generated.

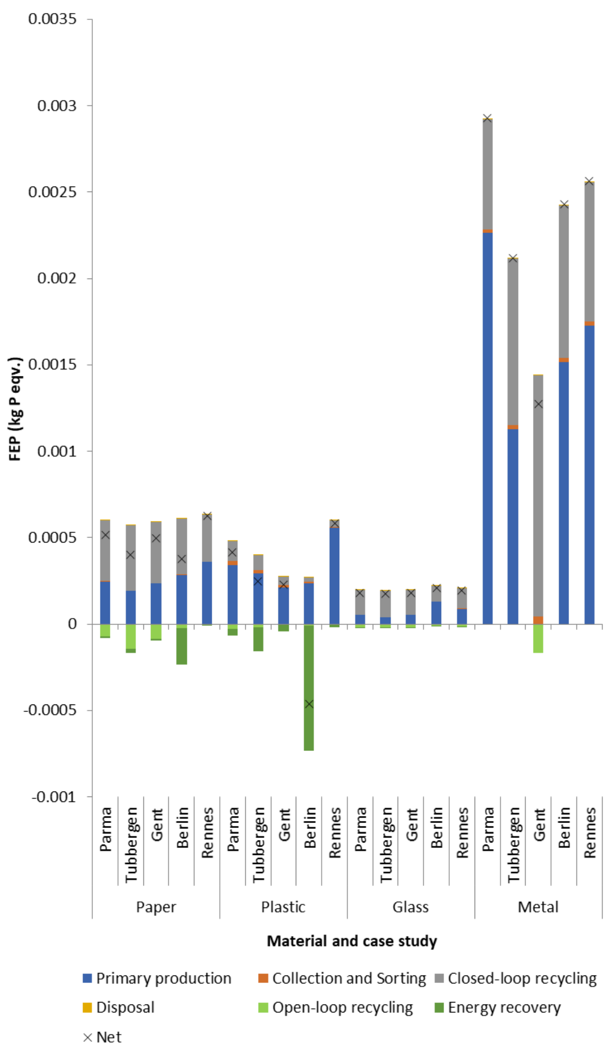

Figure 15: Freshwater eutrophication potential (FEP; kg P-eq.) per kg of each PPW material generated.

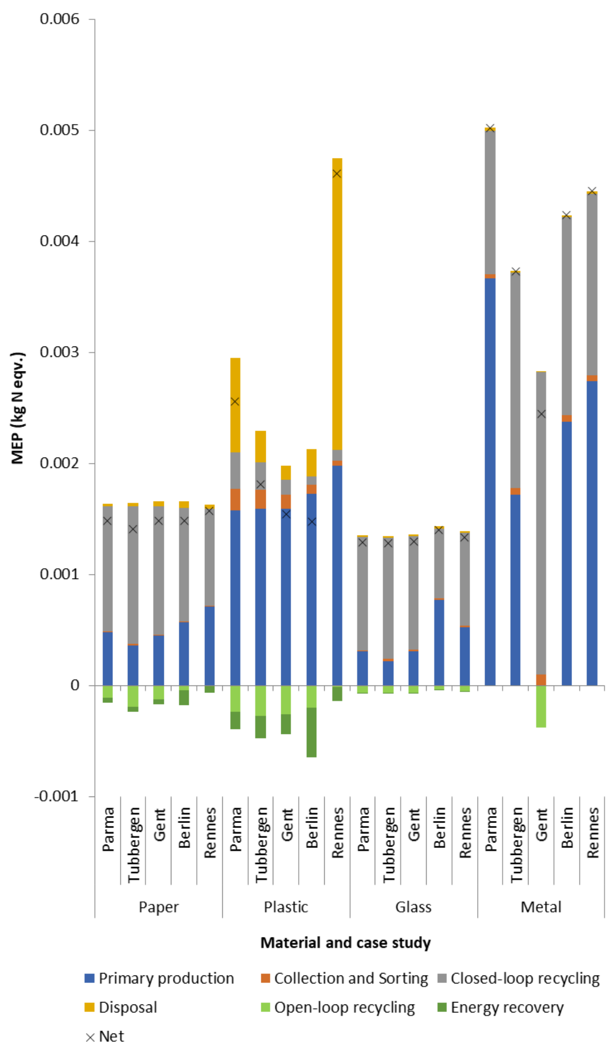

Figure 16: Marine eutrophication potential (MEP; kg N-eq.) per kg of each PPW material generated.

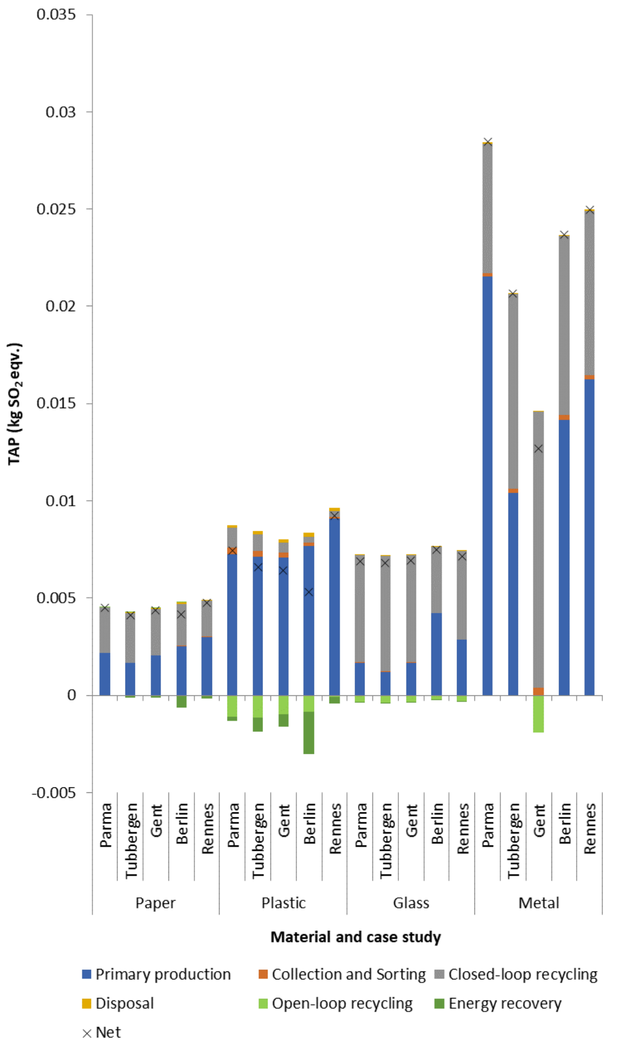

Figure 17: Terrestrial acidification potential (TAP; kg SO_2-eq.) per kg of each PPW material generated.

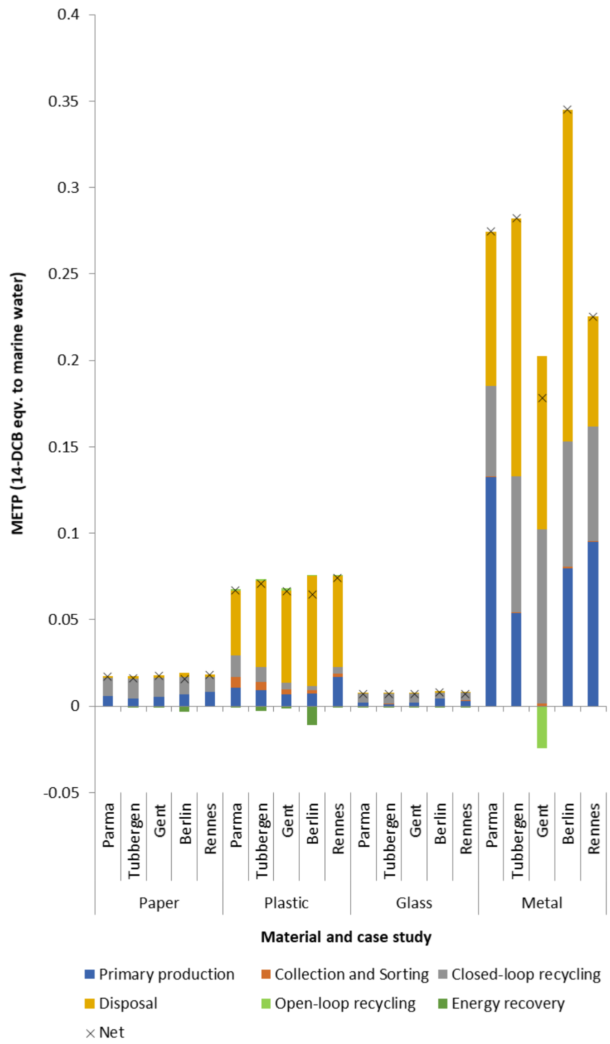

Figure 18: Marine ecotoxicity potential (METP; 1,4 dichlorobenzenes-eq.) per kg of each PPW material generated

3.1.3 Sensitivity analysis

The sensitivity analysis is performed for each case study to investigate the importance of the key system parameters that determine the system-wide losses, i.e. capture rate, sorting efficiency and recycling efficiency. The efficiency of each of these parameters is increased by 10%. While this is a theoretical analysis, the intention is to indicate at which lifecycle stage measures could be most effective, e.g. investing more into the collection infrastructure, reducing the sorting residues through reducing the contamination of separated materials and/or improving the sorting efficiency of sorting facilities, and improving the efficiency of recycling processes. The effects on the total environmental impacts associated with the PPW stream, including the production, collection, sorting, recycling and disposal, are shown for each impact category in Table 1 to Table 5. The gross total is also displayed for each municipality, which shows the total change in each impact category value that would occur if efficiencies at each stage were increased by 10% at the same time. This effect is cumulative, leading potentially to greater environmental reductions than the sum of changes in all the parameters. The observed environmental impacts reduction potentials that can be achieved via systemic waste management improvements differ between impact categories and between the case studies.

3.1.3.1 Parma

Table 1: Sensitivity analysis results for the municipality of Parma: increasing the efficiency of each lifecycle stage by 10%.

		GWP	FDP	FEP	MEP	TAP	METP
Capture rate	Plastic	-0.85%	-1.96%	-0.19%	-2.15%	-0.71%	-0.31%
	Paper	-0.81%	-0.56%	-3.16%	-0.82%	-0.78%	-0.36%
	Composite material	0.05%	0.00%	-0.08%	-0.02%	-0.02%	0.05%
	Metal	-0.82%	-0.66%	-1.26%	-0.59%	-0.93%	-1.71%
	Glass	-0.50%	-0.26%	-0.27%	-0.27%	-0.39%	-0.11%
	Total	**-2.93%**	**-3.44%**	**-4.96%**	**-3.84%**	**-2.83%**	**-2.44%**
Sorting	Plastic	-1.70%	-1.37%	0.03%	-0.14%	-0.64%	-0.85%
	Paper	-0.01%	0.02%	-0.29%	-0.06%	-0.07%	-0.06%
	Glass	-0.67%	-0.35%	-0.36%	-0.36%	-0.52%	-0.15%
	Metal	-0.57%	-0.50%	-0.86%	-0.42%	-0.65%	-1.47%
	Total	**-2.95%**	**-2.20%**	**-1.48%**	**-0.98%**	**-1.89%**	**-2.54%**
Recycling	Plastic	-2.32%	-2.04%	-0.23%	-0.45%	-0.75%	-0.94%
	Paper	0.22%	0.60%	-2.75%	-0.53%	-0.70%	-0.72%
	Total	**-2.11%**	**-1.44%**	**-2.98%**	**-0.99%**	**-1.45%**	**-1.66%**
Gross Total		**-8.73%**	**-7.67%**	**-9.92%**	**-6.05%**	**-6.59%**	**-7.16%**

In Parma, reducing capture losses had the largest effect on the environmental performance of the system compared to reducing sorting or recycling losses. 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 of paper at the recycling stage are associated with increased FDP and 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 (an effect which will become smaller as the energy system becomes more renewable).

The gross total shows how systemic improvements to the waste management, at all three stages (collection, sorting and recycling) can lead to relatively large improvements in Parma. For instance, a 10% improvement in each stage of management for each material will lead to a 8.7% improvement in the associated GWP of the system.

3.1.3.2 Tubbergen

Table 2: Sensitivity analysis results for the municipality of Tubbergen: increasing the efficiency of each lifecycle stage by 10%.

Parameter	Material	GWP	FDP	FEP	MEP	TAP	METP
Collection	Plastic	-1.29%	-1.30%	0.30%	-0.65%	-0.53%	-1.09%
	Paper	0.00%	0.00%	-0.03%	-0.01%	-0.01%	0.00%
	Composite material	0.03%	-0.05%	-0.18%	-0.04%	-0.04%	0.11%
	Metal	-0.39%	-0.31%	-0.69%	-0.26%	-0.46%	-1.33%
	Glass	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	Total	**-1.65%**	**-1.66%**	**-0.60%**	**-0.96%**	**-1.04%**	**-2.32%**
Sorting	Plastic	-1.51%	-1.08%	0.46%	-0.22%	-0.47%	-1.28%
	Paper	-0.01%	0.07%	-0.67%	-0.17%	-0.14%	-0.13%
	Glass	-0.64%	-0.34%	-0.40%	-0.33%	-0.52%	-0.18%
	Metal	-0.27%	-0.23%	-0.47%	-0.19%	-0.32%	-1.21%
	Total	**-2.44%**	**-1.58%**	**-1.07%**	**-0.91%**	**-1.45%**	**-2.80%**
Recycling	Plastic	-2.29%	-1.92%	-0.18%	-0.45%	-0.71%	-1.44%
	Paper	-0.11%	0.73%	-6.72%	-1.68%	-1.38%	-1.29%
	Total	**-2.41%**	**-1.20%**	**-6.90%**	**-2.13%**	**-2.09%**	**-2.74%**
Gross total		**-7.15%**	**-4.96%**	**-8.69%**	**-4.15%**	**-4.82%**	**-8.42%**

In Tubbergen, depending on the environmental impact category, reducing sorting losses and recycling losses have the largest effect on the environmental performance of the system, more than increasing capture rates. In terms of GWP, increasing recycling is more impactful, whereas collection is more important to FDP. Little more paper and glass can be captured in Tubbergen and this is reflected in the negligible changes in the environmental impacts for reduced capture losses of these materials.

In Tubbergen, reduced losses of plastic at the collection and sorting stages leads to reduced plastic incineration and thus reduced energy recovery. Recycling more plastic in the Netherlands, instead of burning it, leads to increased associated FEP.

The gross total shows how systemic improvements to the waste management, at all three stages (collection, sorting and recycling) can lead to considerable improvements in Tubbergen. For instance, a 10% improvement in each stage of management for each material will lead to a 7.15% improvement in the associated GWP of the system.

3.1.3.3 Gent

Table 3: Sensitivity analysis results for the municipality of Gent: increasing the efficiency of each lifecycle stage by 10%.

Parameter	Material	GWP	FDP	FEP	MEP	TAP	METP
Collection	Plastic	-0.75%	-0.61%	0.06%	-0.13%	-0.17%	-0.77%
	Paper	-0.78%	-0.10%	-5.32%	-1.40%	-1.11%	-1.25%
	Composite material	0.02%	-0.02%	-0.07%	-0.02%	-0.02%	0.05%
	Metal	-2.03%	-1.75%	-3.01%	-1.32%	-2.10%	-7.92%
	Glass	-0.80%	-0.46%	-0.42%	-0.39%	-0.57%	-0.23%
	Total	**-4.34%**	**-2.94%**	**-8.75%**	**-3.26%**	**-3.96%**	**-10.11%**
Sorting	Plastic	-0.76%	-0.61%	0.07%	-0.12%	-0.17%	-0.78%
	Paper	-0.08%	-0.01%	-0.54%	-0.14%	-0.11%	-0.13%
	Glass	-1.11%	-0.63%	-0.58%	-0.55%	-0.79%	-0.32%
	Metal	-1.43%	-1.33%	-2.07%	-0.96%	-1.48%	-7.28%
	Total	**-3.38%**	**-2.58%**	**-3.12%**	**-1.76%**	**-2.55%**	**-8.50%**
Recycling	Plastic	-0.98%	-0.89%	0.01%	-0.19%	-0.23%	-0.81%
	Paper	-0.77%	-0.07%	-5.38%	-1.41%	-1.12%	-1.27%
	Total	**-1.75%**	**-0.96%**	**-5.37%**	**-1.60%**	**-1.34%**	**-2.08%**
Gross Total		**-10.07%**	**-6.91%**	**-18.14%**	**-6.98%**	**-8.26%**	**-21.84%**

In Gent, reducing capture losses has the largest effect on the environmental performance of the system compared to reducing sorting or recycling losses. Reduced losses of plastic at the collection and sorting stages lead to reduced plastic incineration and thus reduced energy recovery. Recycling more plastic in Belgium, as in the Netherlands, leads to minor increases in the associated FEP.

The gross total shows how systemic improvements to the waste management, at all three stages (collection, sorting and recycling) can lead to considerable improvements in Gent. For instance, a 10% improvement in each stage of management for each material will lead to a 10% improvement in the associated GWP of the system, the greatest potential improvement in GWP of any of the case studies.

3.1.3.4 Berlin

Table 4: Sensitivity analysis results for the municipality of Berlin: increasing the efficiency of each lifecycle stage by 10%.

Parameter	Material	GWP	FDP	FEP	MEP	TAP	METP
Collection	Plastic	-0.65%	-0.61%	1.32%	-0.17%	-0.11%	-0.49%
	Paper	-0.14%	0.13%	-1.76%	-0.74%	-0.40%	-0.17%
	Composite material	0.01%	-0.01%	-0.07%	-0.01%	-0.01%	0.02%
	Metal	-0.97%	-0.82%	-2.40%	-0.73%	-1.18%	-3.04%
	Glass	-0.40%	-0.22%	-0.34%	-0.22%	-0.33%	-0.09%
	Total	**-2.14%**	**-1.53%**	**-3.25%**	**-1.87%**	**-2.04%**	**-3.77%**
Sorting	Plastic	-0.71%	-0.55%	1.54%	-0.07%	-0.08%	-0.51%
	Paper	0.00%	0.03%	-0.12%	-0.07%	-0.03%	-0.02%
	Glass	-0.40%	-0.22%	-0.34%	-0.22%	-0.33%	-0.09%
	Metal	-0.68%	-0.62%	-1.64%	-0.52%	-0.83%	-2.79%
	Total	**-1.78%**	**-1.36%**	**-0.57%**	**-0.89%**	**-1.28%**	**-3.40%**
Recycling	Plastic	-1.12%	-0.97%	-0.04%	-0.26%	-0.33%	-0.71%
	Paper	0.01%	0.29%	-1.21%	-0.71%	-0.32%	-0.15%
	Total	**-1.11%**	**-0.68%**	**-1.25%**	**-0.97%**	**-0.65%**	**-0.86%**
Gross Total		**-5.45%**	**-3.88%**	**-5.27%**	**-3.96%**	**-4.19%**	**-8.54%**

In Berlin, reducing capture losses has the largest effect on the environmental performance of the system compared to reducing sorting or recycling losses. Reduced losses of plastic at the collection and sorting stages leads to reduced plastic incineration with energy recovery. Recycling more plastic in Germany, as in the Netherlands and Belgium, leads to increased associated FEP.

The gross total shows how systemic improvements to the waste management, at all three stages (collection, sorting and recycling) will lead to a 5.5% improvement in the associated GWP of the system.

3.1.3.5 Rennes

Table 5: Sensitivity analysis results for the municipality of Rennes: increasing the efficiency of each lifecycle stage by 10%.

		GWP	FDP	FEP	MEP	TAP	METP
Capture rate	Plastic	0.03%	-0.37%	-0.06%	-0.74%	-0.13%	0.14%
	Paper	-0.48%	-0.36%	-1.56%	-0.36%	-0.36%	-0.15%
	Composite material	0.01%	-0.02%	-0.06%	-0.02%	-0.02%	0.05%
	Metal	-0.87%	-0.67%	-1.39%	-0.55%	-0.97%	-2.01%
	Glass	-0.79%	-0.40%	-0.45%	-0.37%	-0.61%	-0.20%
	Total	**-2.10%**	**-1.81%**	**-3.53%**	**-2.04%**	**-2.09%**	**-2.17%**
Sorting	Plastic	-0.11%	-0.08%	0.00%	-0.01%	-0.03%	-0.07%
	Paper	-0.22%	-0.05%	-1.48%	-0.30%	-0.28%	-0.31%
	Glass	-0.79%	-0.40%	-0.45%	-0.37%	-0.61%	-0.20%
	Metal	-0.61%	-0.51%	-0.96%	-0.39%	-0.68%	-1.71%
	Total	**-1.72%**	**-1.03%**	**-2.88%**	**-1.07%**	**-1.60%**	**-2.30%**
Recycling	Plastic	-0.37%	-0.33%	-0.06%	-0.05%	-0.13%	-0.10%
	Paper	-0.23%	-0.06%	-1.54%	-0.31%	-0.29%	-0.32%
	Total	**-0.60%**	**-0.39%**	**-1.60%**	**-0.36%**	**-0.42%**	**-0.42%**
Gross total		**-4.69%**	**-3.40%**	**-8.62%**	**-3.65%**	**-4.35%**	**-5.20%**

In Rennes, reducing capture losses has the largest effect on the environmental performance of the system compared to reducing sorting or recycling losses. Reduced capture losses of plastic leads to an increased GWP associated with PPW in Rennes. The loss of plastic at the sorting stage is substantial, due to the PMD + Fibres commingling collection system employed by the municipality. In addition, the incineration rate of residual waste is low, relative to other municipalities. Since 100% of the waste lost at the sorting stage is incinerated, the amount of plastic incineration will actually be increased if capture losses are reduced in Rennes, leading to increased GWP.

The gross total shows how systemic improvements to the waste management, at all three stages (collection, sorting and recycling) can lead to a 4.4% improvement in the associated GWP of the system. This is the lowest improvement in GWP of the 5 PPW case studies; this is reflective of Rennes current performance, but also the PMD + Fibres commingling collection method.

3.1.4 Discussion

Collectively, the EU member states generated 73 million tonnes of paper and packaging waste (PPW) in 2016 (Eurostat, 2016). As has been highlighted in previous COLLECTORS reports, the current trend of increasing capture rates of the PPW streams is promising, but progress varies considerably between the members States and regions.

Good regional practices have the potential to serve as good examples for other regions and go some way to achieving European recycling rate targets, these are: 85% for paper, 55% for plastic packaging, 60% for aluminium, 80% for ferrous metal and 75% for glass by 2030 (European Commission, 2018). An advantage of assessing the WCS with a broad systemic perspective, as is recommended in D3.1 and applied here, is that it is possible to determine how far from meeting these targets each assessed municipality currently is. Recycling rates should be calculated based on the weight of packaging waste which enters the recycling stage (European Commission, 2018). Since the model presented considers post collection losses of material at the sorting stage, it is possible to determine which case studies may be used as good examples for collecting a particular material. Tubbergen achieves capture rates that already meet these 2030 targets for paper and glass and Gent achieves capture rates that already meet the 2030 targets for glass and metal, and collects almost enough paper to meet the 2030 recycling target for paper. Parma collects almost enough plastic and glass to meet these targets.

Across the case studies, plastics were the largest contributor to the total GWP, FDP and METP. The largest contributor to the total FEP, MEP and TAP was paper. Metal is the largest contributor to the total METP. This is despite metal having the highest associated impacts per kg of generated waste compared to the other PPW materials for most impact categories. The relatively lower total impacts of metal presented in most cases is due to the quantities of the PPW materials generated.

The FEP associated with PPW is shown to increase with reduced plastic losses in several case studies. This can be attributed to the additional energy requirement associated with the recycling processes. Parma and Rennes did not follow this rule. The reason for this is that both Parma and Rennes have relatively low residual waste incineration rates; decreased plastic capture losses result in relatively greater losses at the sorting and recycling stages and, as the material lost at the sorting and recycling stages is all incinerated, lower capture losses result in increased incineration. The FEP associated with conventional energy production is also relatively lower in Parma and Rennes compared to other case studies, so the potential avoided impacts associated with the incineration of PPW material are lower than the other case studies. Decreasing sorting losses thus leads to reduced impacts, as incineration is a less favourable option. In addition, the low FEP associated with conventional energy production in Belgium and France is the reason Gent and Rennes do not show increased FEP with decreased paper losses (and decreased energy recovery from paper) at the recycling stage. As Europe moves towards harnessing more green energy and incinerating waste becomes a less environmentally beneficial alternative, these results indicate the importance of improving recycling rates by reducing material losses at the sorting stage.

Parma, Berlin, Gent and Berlin collect plastic, metal and composite material together using a PMD commingling method, whereas Rennes uses a PMD + Fibres commingling method (section 1.6.1.1). Commingling collection methods are generally considered to be less costly and more convenient than the single source separation method, which frequently leads to increased community participation (Miranda, et al., 2013; Cimpan, et al., 2015). Rennes has relatively lower capture rates for paper and plastic, being the only municipality to have a greater reduction in the GWP associated with plastic with reduced capture losses than with reduced sorting losses. In fact, the COLLECTORS database (COLLECTORS, 2019) reveals that, on average, the PMD + Fibres commingling method results in lower capture rates than the PMD commingling method for every material (Appendix Table B-4). There is no obvious reason for this, but a possible explanation may lie in the behaviour of citizens and how they associate environmental issues with the separation of their waste. There is a significant country effect on the capture rates of each PPW observed in the database. Hence, countries with municipalities with higher capture rates may have better waste management policies, better informed citizens and thus better collection performance. More research is needed in order to understand these social factors, but it is clear that when there is a strong conviction both about the benefits of recycling and the responsibility of cooperating, people are more willing to participate (Vicente & Reis, 2008).

As well as having lower capture rates for paper and plastic, the model (based on the COLLECTORS database (COLLECTORS, 2019)) also assumed Rennes to have relatively high losses of these materials at the sorting stage compared to the other municipalities, which is likely due to the increased contamination of both these materials when they are collected together (Eriksen, et al., 2018). This results in Rennes losing more than half of the plastic that is collected before it can be recycled, leading to a reduced recycling rate for plastic. Whilst more research is needed to understand what would be the best strategy to improve PPW collection in Rennes, the model presented here suggests that replacing the PMD + Fibres commingling collection method with a PMD commingling method could more than double the recycling rate for plastic. This consequence is attributed to reduced sorting losses only, and does not account for the possible increased capture rate that could be achieved using PMD commingling. This could be achieved by simply providing an additional container per household or additional bring points that are designated for paper.

Out of the five case studies presented here, the best capture rates are achieved when PMD commingling is employed in conjunction with a PAYT system. The analysis didn't consider the maturity of the systems, e.g. for how long they have been in place, nor did it consider the specifics of the management policies themselves (e.g. the type of PAYT). Whilst the difference in the environmental impacts associated with each PPW material between each municipality are confounded by the impacts associated with residual waste management (e.g. incineration rates) and the avoided impacts associated with energy recovery, it is clear that increased recycling rates result in lower environmental impacts for all materials in most impact categories. It is also clear that the collection and sorting processes contribute only small amounts in the life cycle of the materials. Thus, additional investments in the PPW collection infrastructure of municipalities will – despite expected small increases in the environmental impacts associated with the collection and sorting – likely result in lower overall environmental impacts when looked at the system holistically from a life cycle perspective.

3.2Waste Electrical and Electronic Equipment

3.2.1 Material flows

3.2.1.1 Pembrokeshire

The municipality of Pembrokeshire reported to have collected an estimated 399 tonnes and 589 tonnes of small WEEE in 2013 and 2018 respectively, meaning that the capture rate for small WEEE increased from 32% to 40% in this timeframe. An estimated 201 tonnes and 276 tonnes of IT equipment were collected in these years with a capture rate of 46% and 59% respectively. An estimated 3.5 tonnes and 3.8 tonnes of lamps were collected in these years with a capture rate of 9.1% and 11% respectively. Of the WEEE that is not collected by a designated WCS, 70% of WEEE has an unknown fate (Urban Mine Platform, 2018). It is believed that the improvements made during this time are in part due to local campaigns run by REPIC. In July 2018, "Green Shed" reuse centres opened; whilst it is unclear if these centres made an impact to the results over the time frame, it is thought that these should increase collection rate of small WEEE, IT & lamps in the coming years. Pembrokeshire also increased the efficiency of transportation by 15% during this period of time.

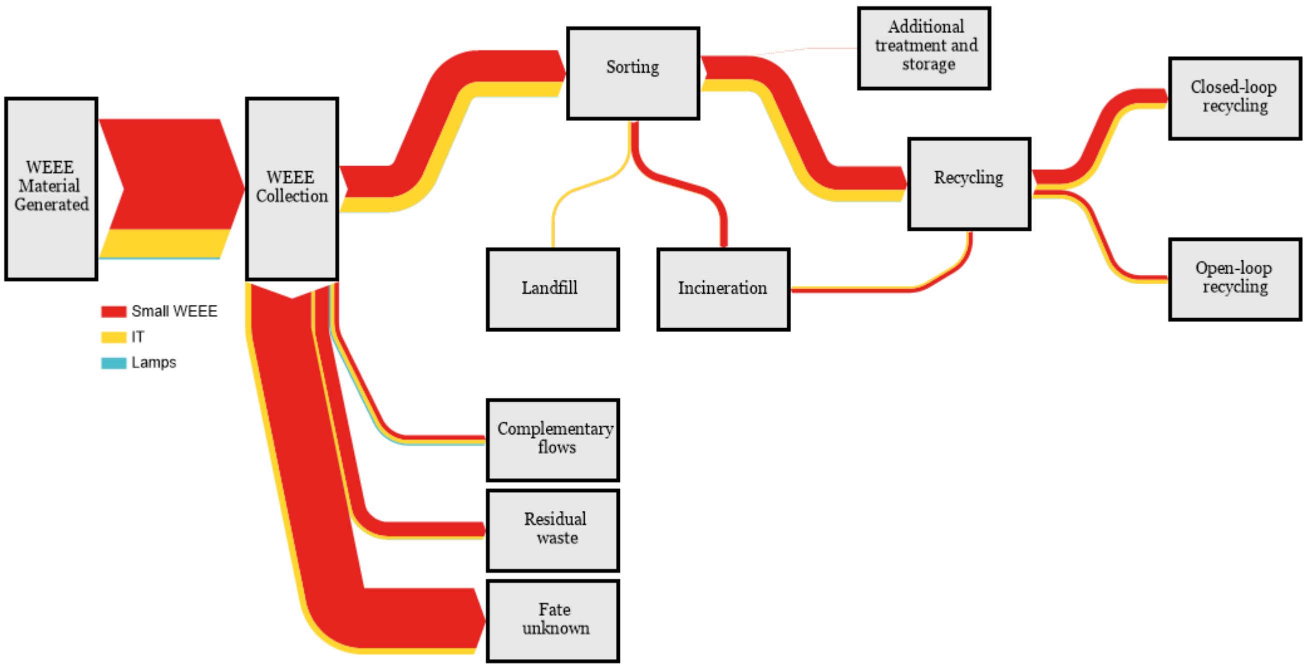

Figure 19: WEEE material flows in the municipality of Pembrokeshire (reflecting the situation after improvements)

3.2.1.2 Helsinki

The municipality of Helsinki reported to have collected an estimated 2136 tonnes and 2625 tonnes of small WEEE in 2011 and 2015 respectively, meaning that the capture rate for small WEEE increased from 36% to 41% in this timeframe. An estimated 752 tonnes and 1113 tonnes of IT equipment were collected in these years with a capture rate of 42% and 61% respectively. An estimated 47 tonnes and 63 tonnes of lamps were collected in these years with a capture rate of

18% and 23% respectively. Of the WEEE that is not collected by a designated WCS, 71% of WEEE has an unknown fate (Urban Mine Platform, 2018). Higher collection quantities achieved over this time period are likely due to diversification of bring points and an increased collection network density. Helsinki also increased the efficiency of the transportation of WEEE by 30% over this time period.

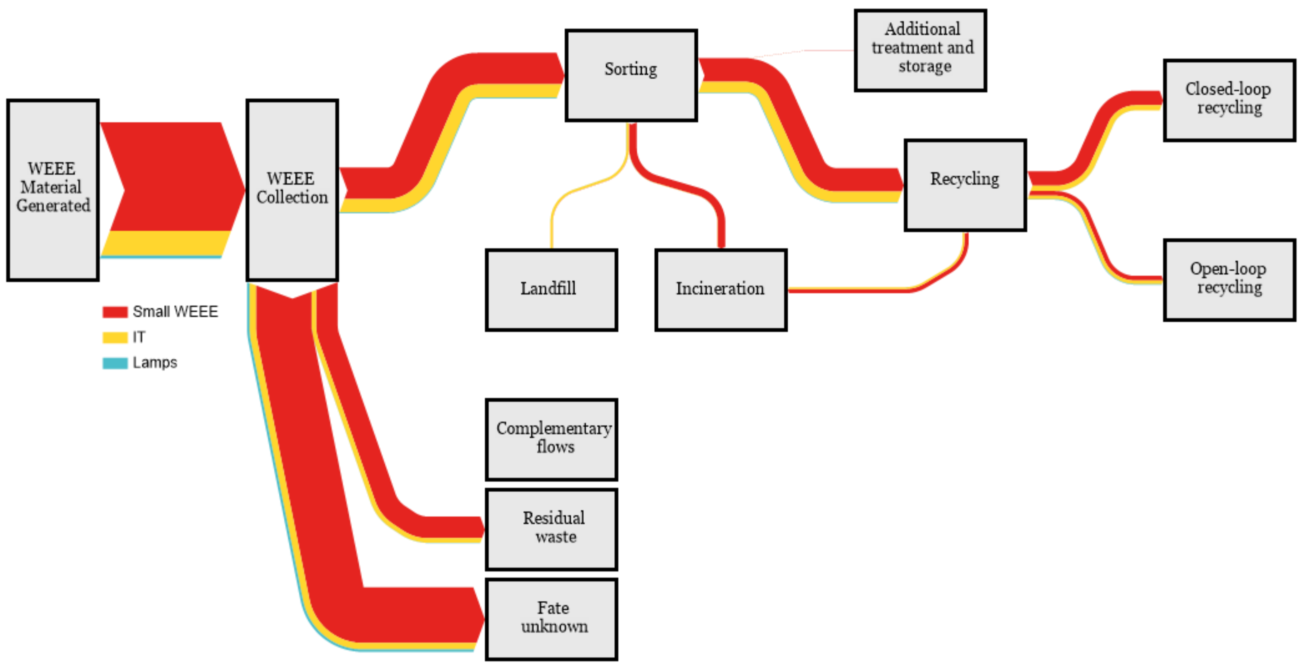

Figure 20: WEEE material flows in the municipality of Helsinki (reflecting the situation after improvements)

3.2.1.3 Genova

The municipality of Genova reported to have collected an estimated 231 tonnes and 384 tonnes of small WEEE in 2012 and 2016 respectively, meaning that the capture rate for small WEEE increased from 9.0% to 15% in this timeframe. An estimated 65 tonnes and 108 tonnes of IT equipment were collected in these years with a capture rate of 9.1% and 15% respectively. An estimated 4.5 tonnes and 6.2 tonnes of lamps were collected in these years with a capture rate of 5.4% and 8.6% respectively. Of the WEEE that is not collected by a designated WCS, 79% of WEEE has an unknown fate (Urban Mine Platform, 2018). Improvements can be attributed, in part, to the WEEENMODELS project, which involved the creation of 47 new mobile collection points for small WEEE and 4 ecological islands. In addition, an effective communication campaign has been carried out by AMIU and involving retailers allowed the message to reach a wider community.

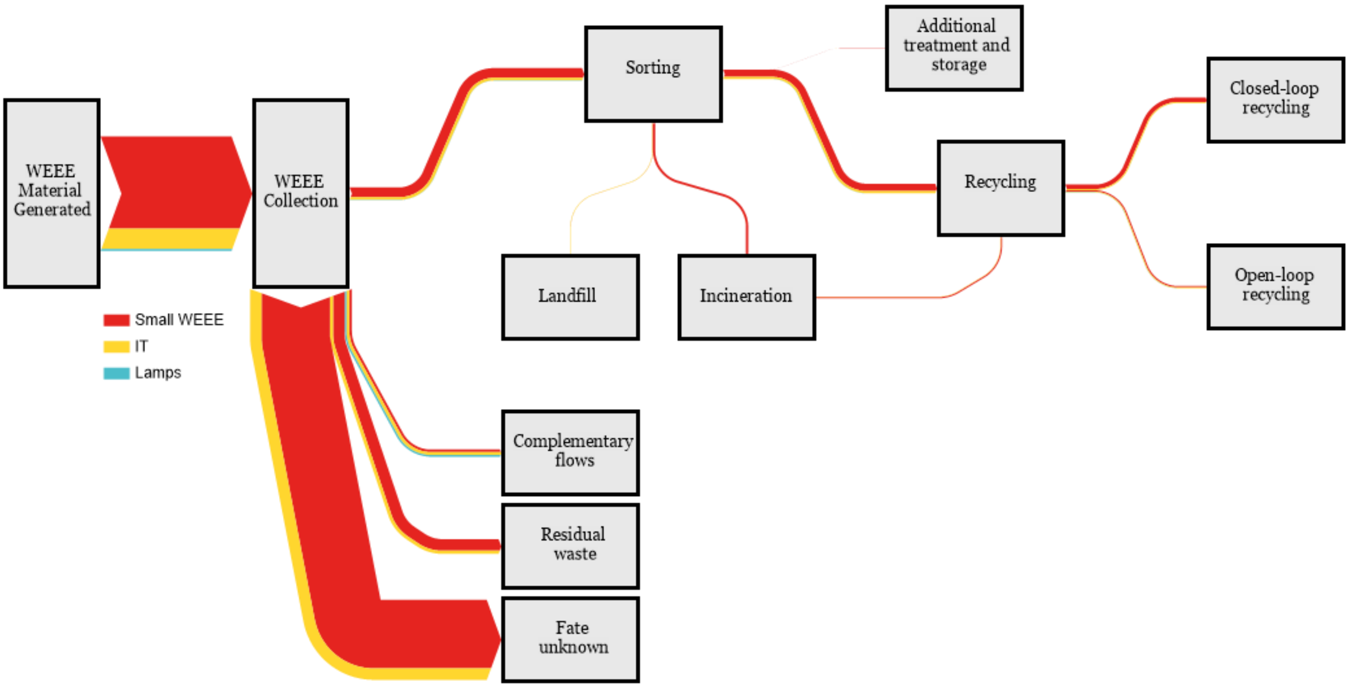

Figure 21: WEEE material flows in the municipality of Genova (reflecting the situation after improvements)

3.2.1.4 Cyclad

The municipality of Cyclad reported to have collected an estimated 482 tonnes and 736 tonnes of small WEEE in 2015 and 2017 respectively, meaning that the capture rate for small WEEE increased from 61% to 73% in this timeframe. An estimated 118 tonnes and 195 tonnes of IT equipment were collected in these years with a capture rate of 61% and 73% respectively. It is assumed that no lamps were collected in a dedicated WEEE WCS in 2015. In 2017, 3 tonnes of lamps were collected, giving Cyclad a capture rate of 14% for lamps. Of the WEEE that is not collected by a designated WCS, 78% of WEEE has an unknown fate (Urban Mine Platform, 2018). Increased capture rates of WEEE in Cyclad are likely the result of a legal ban on cash transaction for metals which helps prevent WEEE leakage via complementary flows or other fates; this has been paired with improved security at the CAS, i.e. locked containers and camera surveillance.

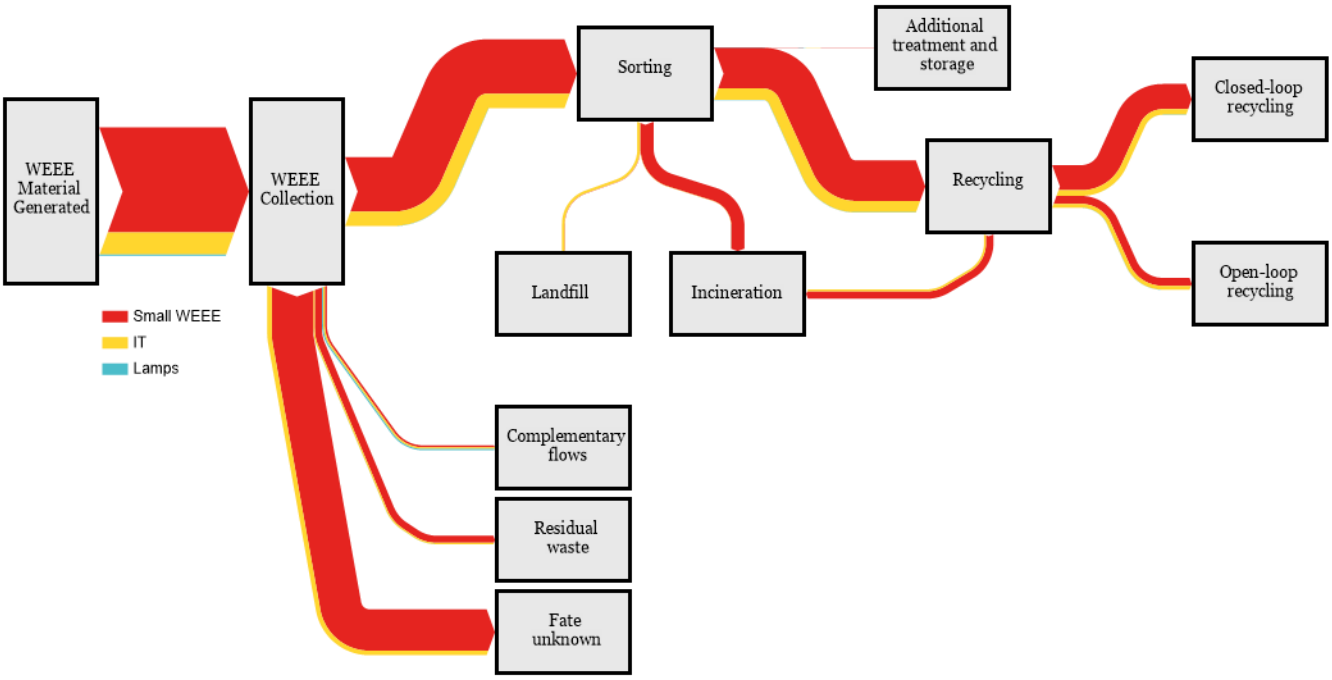

Figure 22: WEEE material flows in the municipality of Cyclad (reflecting the situation after improvements)

3.2.1.5 Vienna

The municipality of Vienna reported to have collected an estimated 2397 tonnes and 3677 tonnes of small WEEE in 2010 and 2015 respectively, meaning that the capture rate for small WEEE increased from 20% to 29% in this timeframe. An estimated 2220 tonnes and 2465 tonnes of IT equipment were collected in these years with a capture rate of 57% and 60% respectively. An estimated 89 tonnes and 159 tonnes of lamps were collected in these years with a capture rate of 33% and 55% respectively. Of the WEEE that is not collected by a designated WCS, 66% of WEEE has an unknown fate (Urban Mine Platform, 2018).

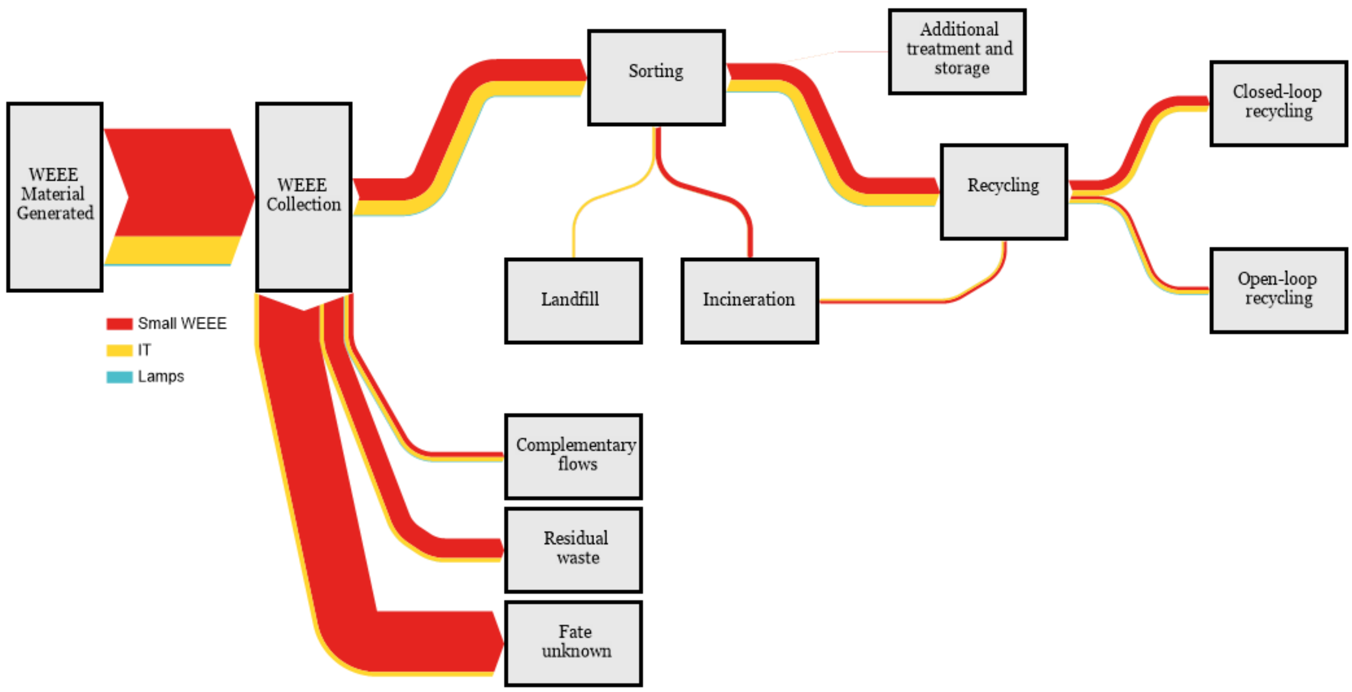

Figure 23: WEEE material flows in the municipality of Vienna (reflecting the situation after improvements)

3.2.2 Environmental impacts

3.2.2.1 Environmental impacts of each WEEE category

The environmental impact values associated with the functional unit (1 kg of waste generated for each WEEE category) for each impact category are similar between the case studies (Figure 24 to Figure 29, where "x" represents the net impact including substitution). Lamps have the lowest environmental impacts for each environmental impact category. IT has the largest environmental impact for every category apart from MEP, which is highest for small WEEE.

In most cases, the production of the constituent materials of electrical and electronic equipment is the largest contributor to the environmental impacts of the WEEE, although in some cases the disposal is the most important factor (i.e. MEPT associated with small WEEE in Cyclad and IT in Helsinki and Vienna). As with PPW, the environmental impacts associated with collection and sorting of WEEE is only a small portion of the overall impact for each impact category; this ranges from 0.01% MEP to 0.8% FDP for small WEEE on average, from 2.6% FPD to 0.6% MEP for IT, and from 8.9% FEP to 2.6% METP for lamps.

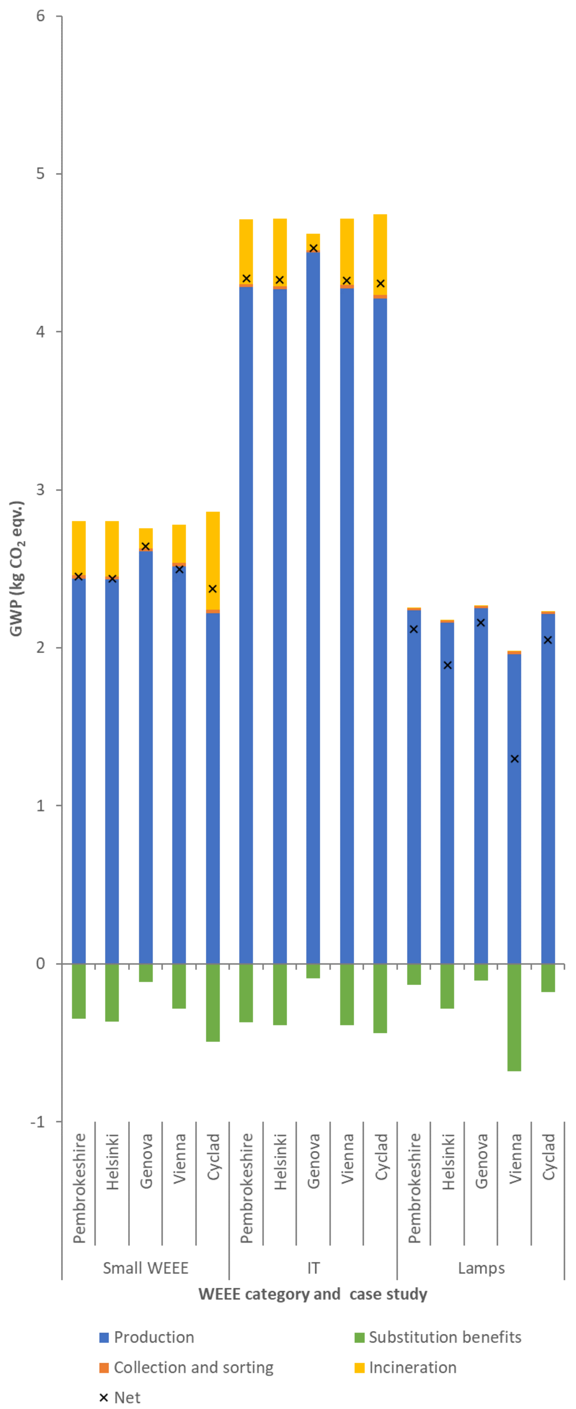

Figure 24: Global warming potential (GWP; kg CO_2-eq.) per kg of waste generated for each WEEE category.

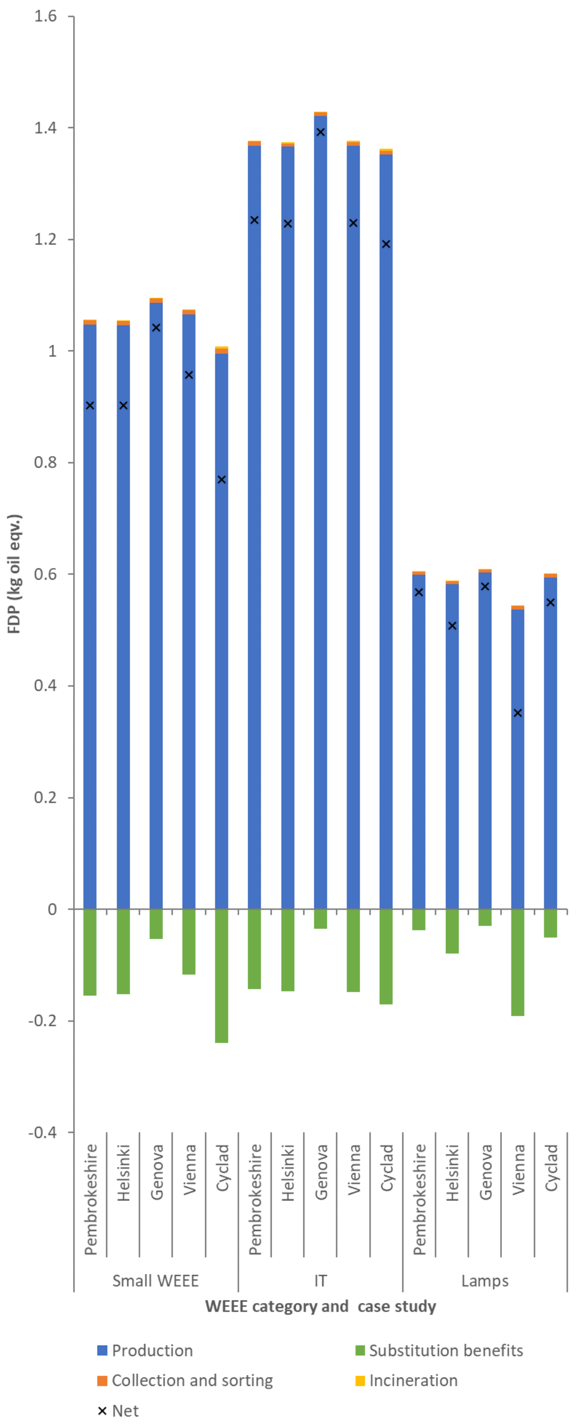

Figure 25: Fossil depletion potential (FDP), calculated as the equivalent energy based on the upper heating value of crude oil, (42 MJ per kg, in ground) per kg of waste generated for each WEEE category.

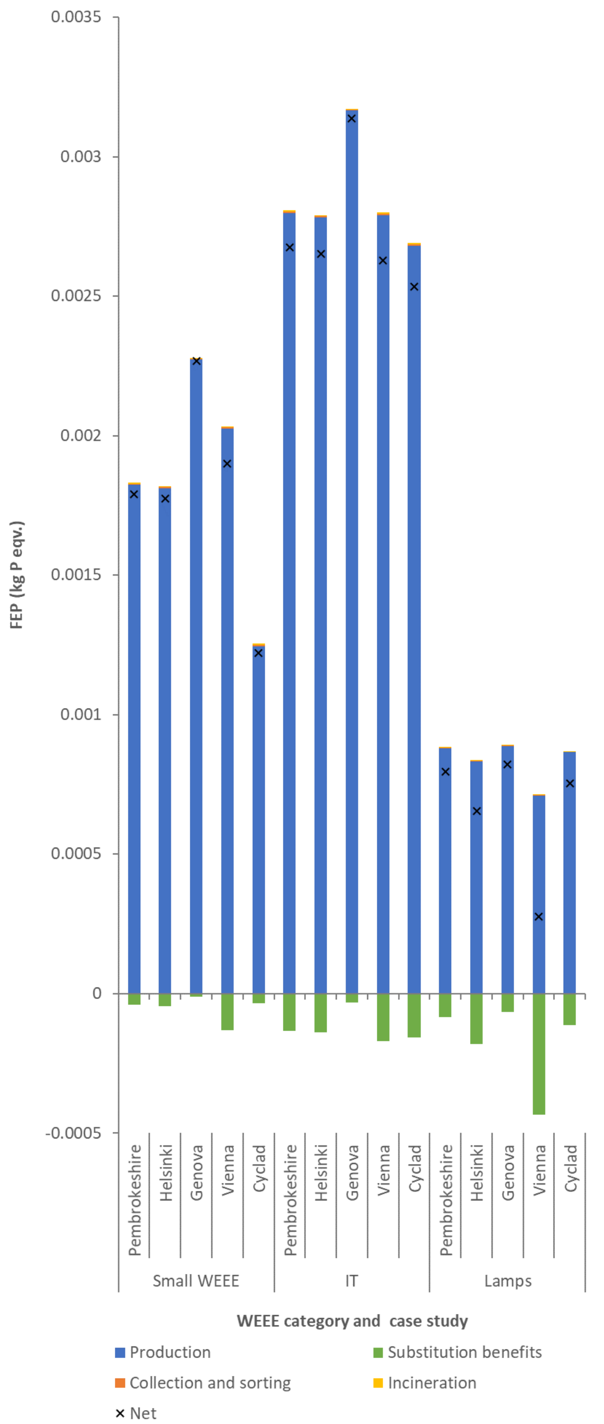

Figure 26: Freshwater eutrophication potential (FEP; kg P-eq.) per kg of waste generated for each WEEE category.

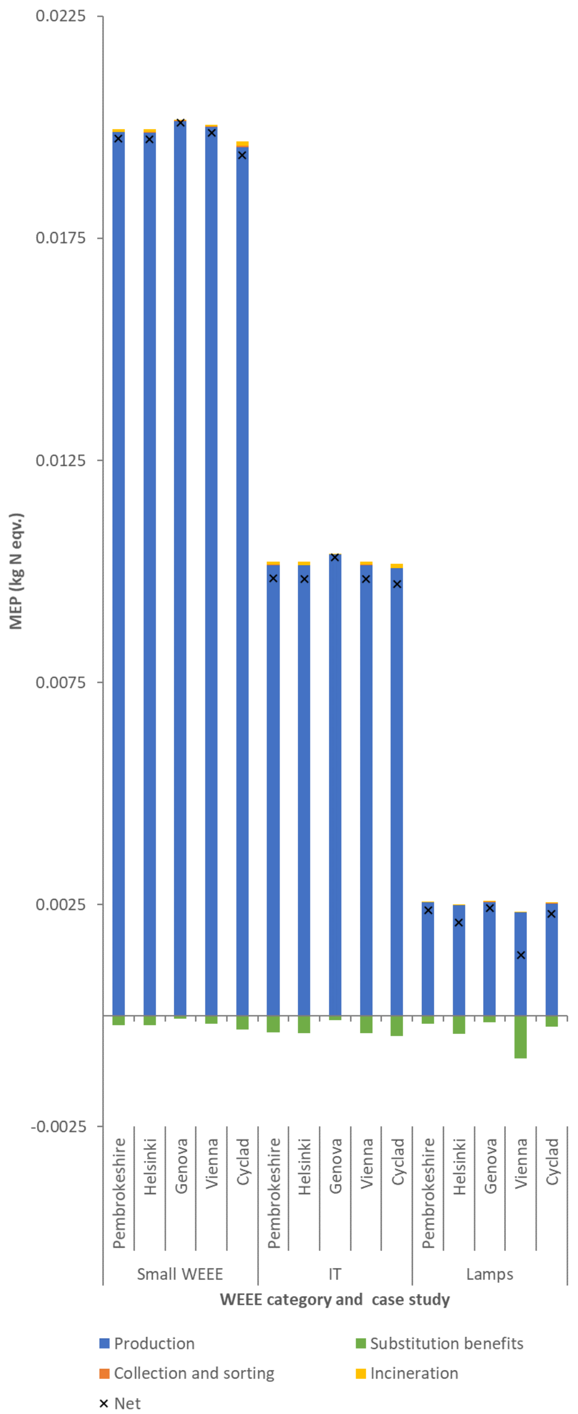

Figure 27: Marine eutrophication potential (MEP; kg N-eq.) per kg of waste generated for each WEEE category.

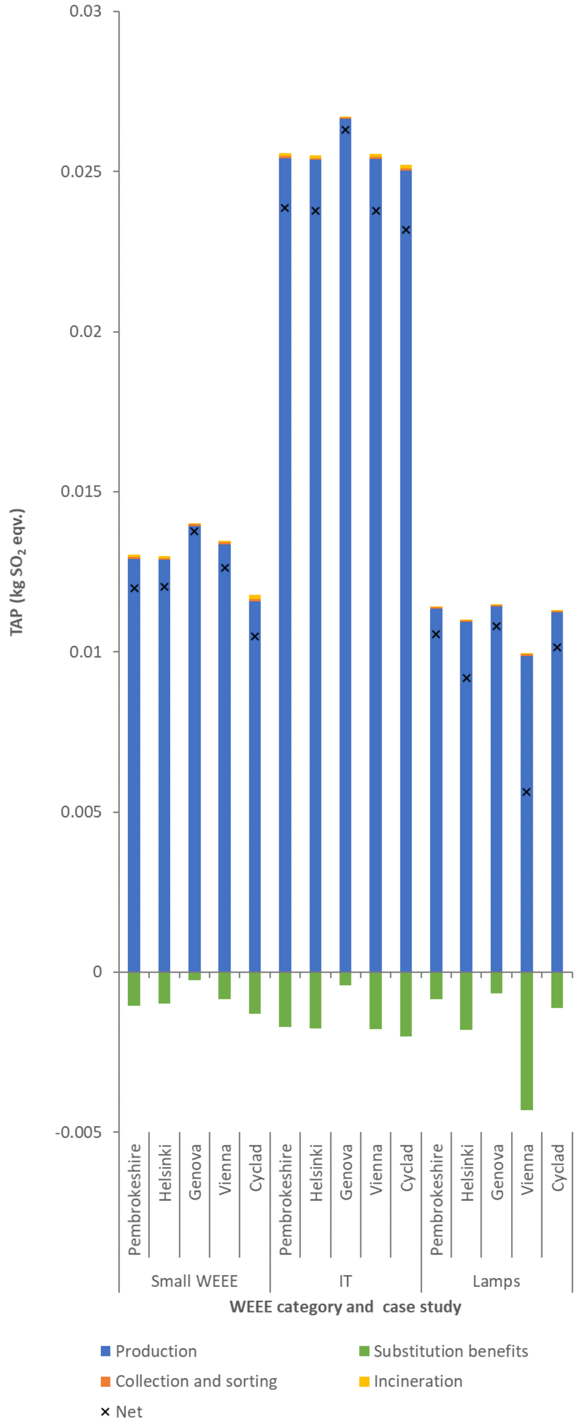

Figure 28: Terrestrial acidification potential (TAP; kg SO_2-eq.) per kg of waste generated for each WEEE category.

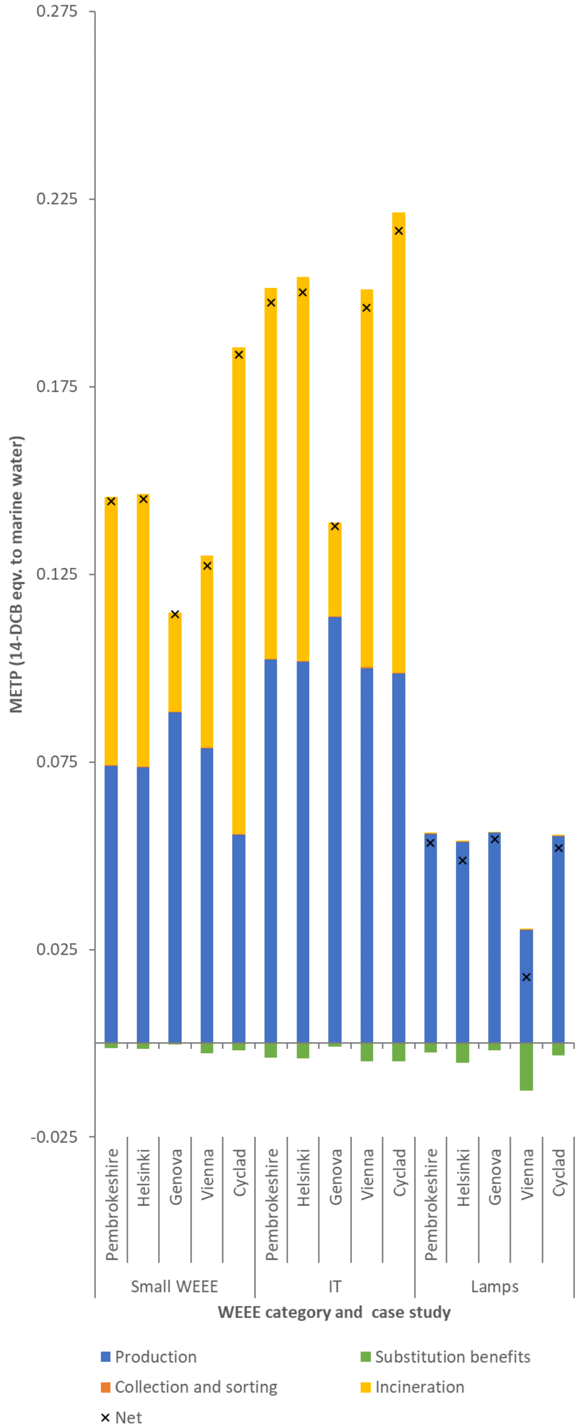

Figure 29: Marine ecotoxicity potential (METP; 1,4 dichlorobenzenes-eq.) per kg of waste generated for each WEEE category.

3.2.2.2 Delta analysis

Delta analysis is a tool for performing variance analysis on dimensional data. You can use delta analysis to compare data from two different scenarios or points in time to calculate the variances and percent variances. Thus, you can analyse the effects of changes in the performance of WEEE collection between two different years. For the COLLECTORS project, delta analysis is performed as part of the assessment of the circular economy, the cost benefit analysis and here as part of the LCA. We analyse the change in performance between two different years, before and after improvement actions were taken that attempt to increase WEEE capture rates (discussed in section 2.1.2.2). The change in the management of each WEEE category specifically is assessed.

The results are shown in Figure 30 to Figure 35[2]. In each case study, there has been an increase in the capture rates of each WEEE category between the two years of interest. This has resulted in an increase in the impacts associated with incineration per kg of waste generated for each WEEE category. The avoided impacts associated with substitution benefits (i.e. energy capture and open-loop recycling) have increased with increased capture rates, reducing the overall impacts of each WEEE category. The impacts associated with production have been decreased in each case, due to the increased amount of metal and precious metals entering closed-loop recycling. The impacts associated with collection and sorting have increased and decreased depending on the case study. This is because increased capture rates increase the collection and sorting activity associated with each kg of waste generated, as it does for the PPW. However, this increase is mitigated in some cases by an increase in the collection efficiency of the WCS (e.g. for efficient trucks, transport routes etc.).

In this study, the reductions in the net environmental impacts associated with the WEEE are small. Although the production of all the WEEE generated is considered, the collection and sorting and the inputs and outputs of treating the waste during disposal and recycling are only considered for the WEEE collected in designated WEEE WCS. Thus, increased capture rates lead to both increased substitution benefits and increased environmental impacts associated with the waste treatment.

[2] * in the Figures: for Cyclad, no change in the avoided impacts and incineration of lamps is reported (Figure 30 to Figure 35). This is because at the first time point (2015), no lamps were reported to be collected, thus the avoided impacts and impacts associated with the incineration of the recovered material in 2015 for lamps were 0. Thus, Delta analysis has not been performed for these life cycle stages in Cyclad.

More research is needed in order to understand the potential benefits or further environmental impacts associated with the complementary flows and the WEEE entering the residual waste. There is also a large amount of WEEE with an unknown fate. No environmental impacts were associated with the WEEE that did not enter the WEEE WCS.

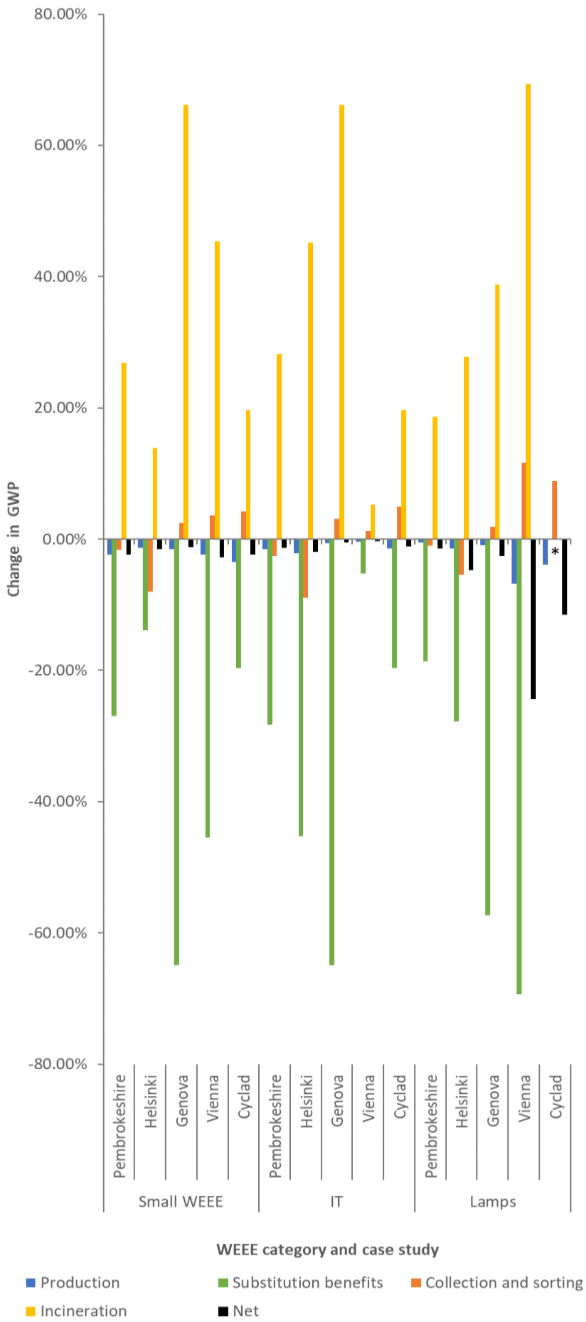

Figure 30: Percentage change in the GWP per kg of waste, generated for each WEEE category, between different years for each case study (before and after improvement actions).

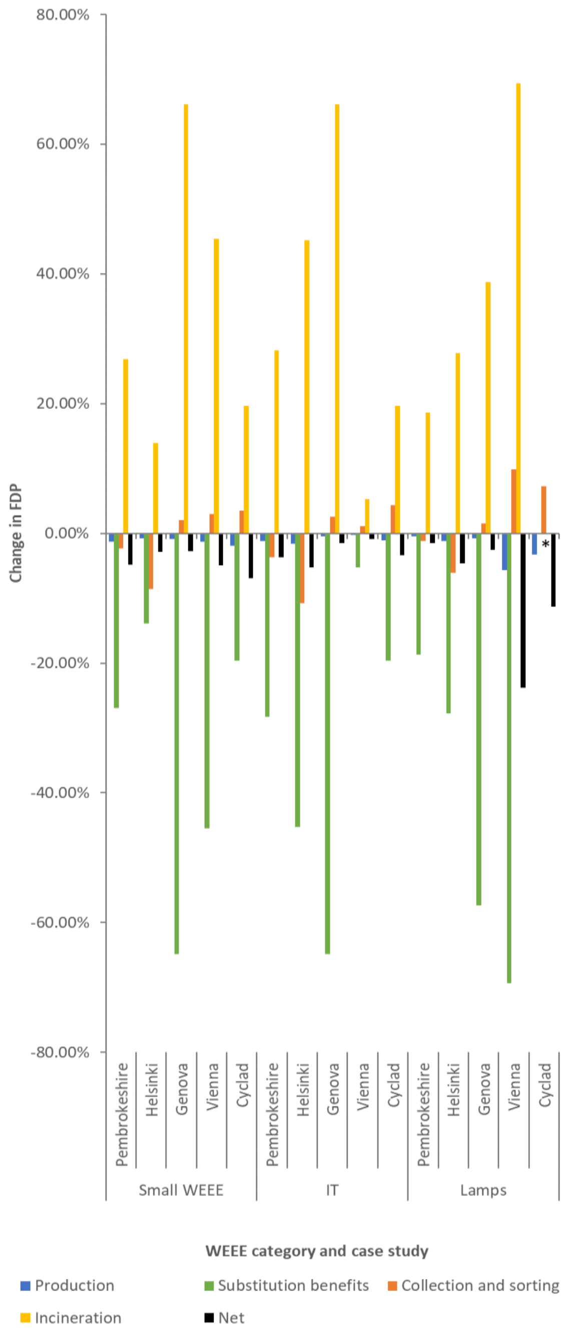

Figure 31: Percentage change in the FDP per kg of waste, generated for each WEEE category, between different years for each case study (before and after improvement actions).

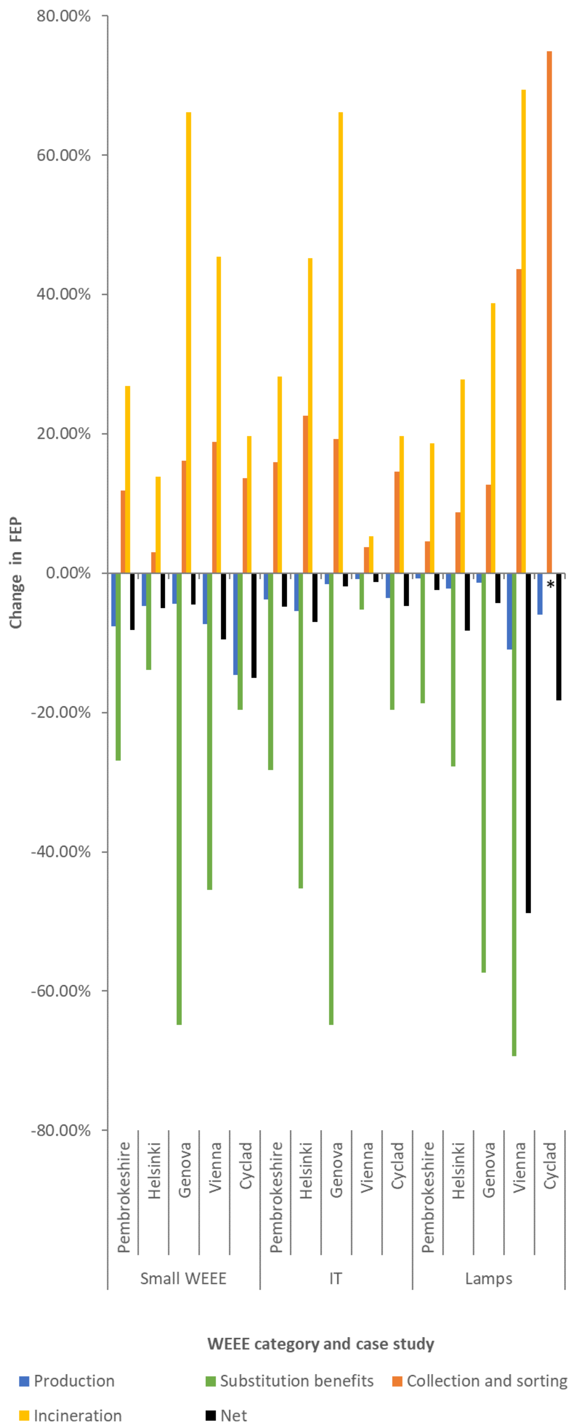

Figure 32: Percentage change in the FEP per kg of waste, generated for each WEEE category, between different years for each case study (before and after improvement actions).

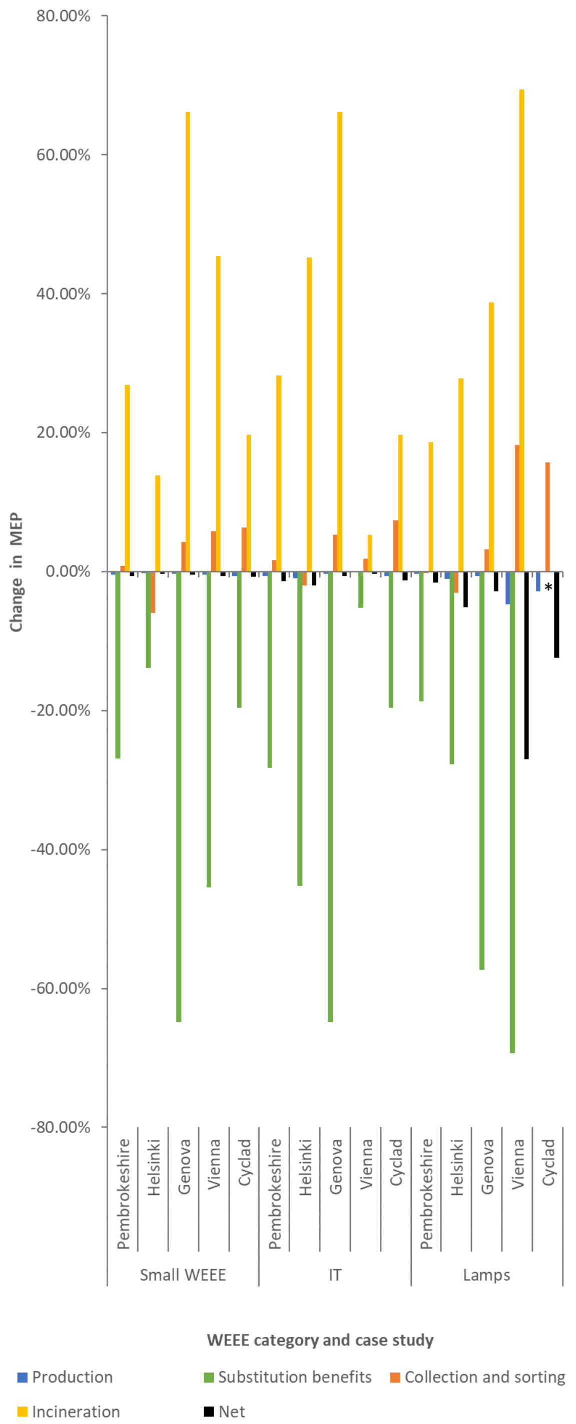

Figure 33: Percentage change in the MEP per kg of waste, generated for each WEEE category, between different years for each case study (before and after improvement actions).

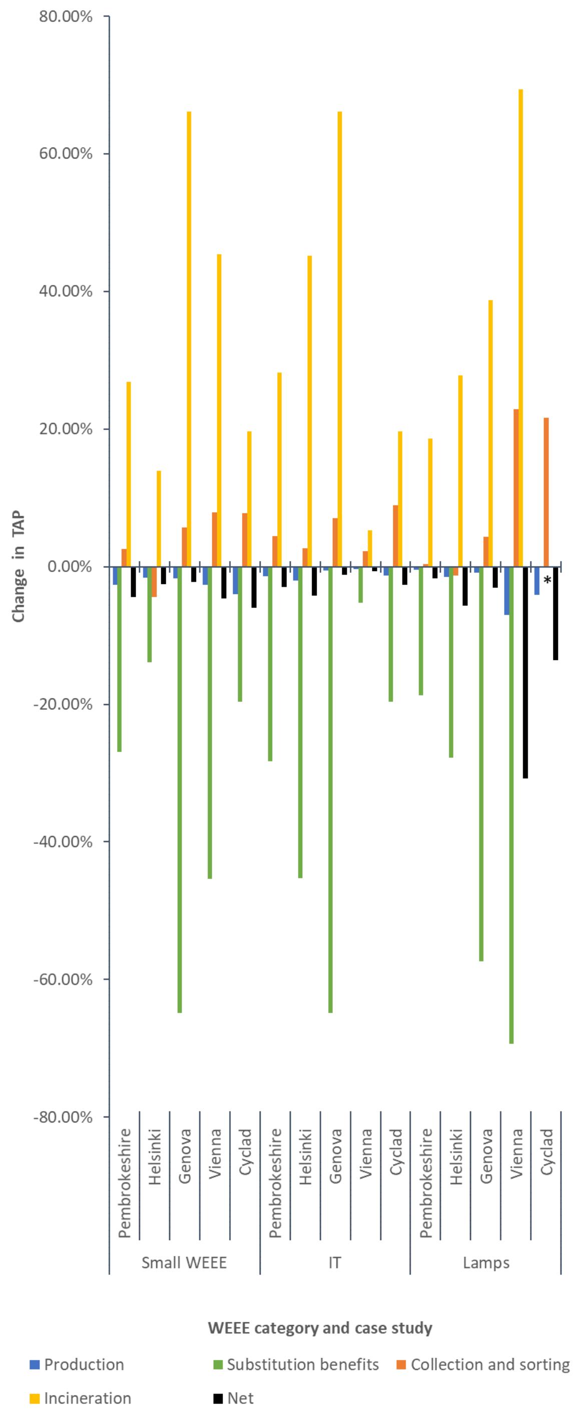

Figure 34: Percentage change in the TAP per kg of waste, generated for each WEEE category, between different years for each case study (before and after improvement actions).

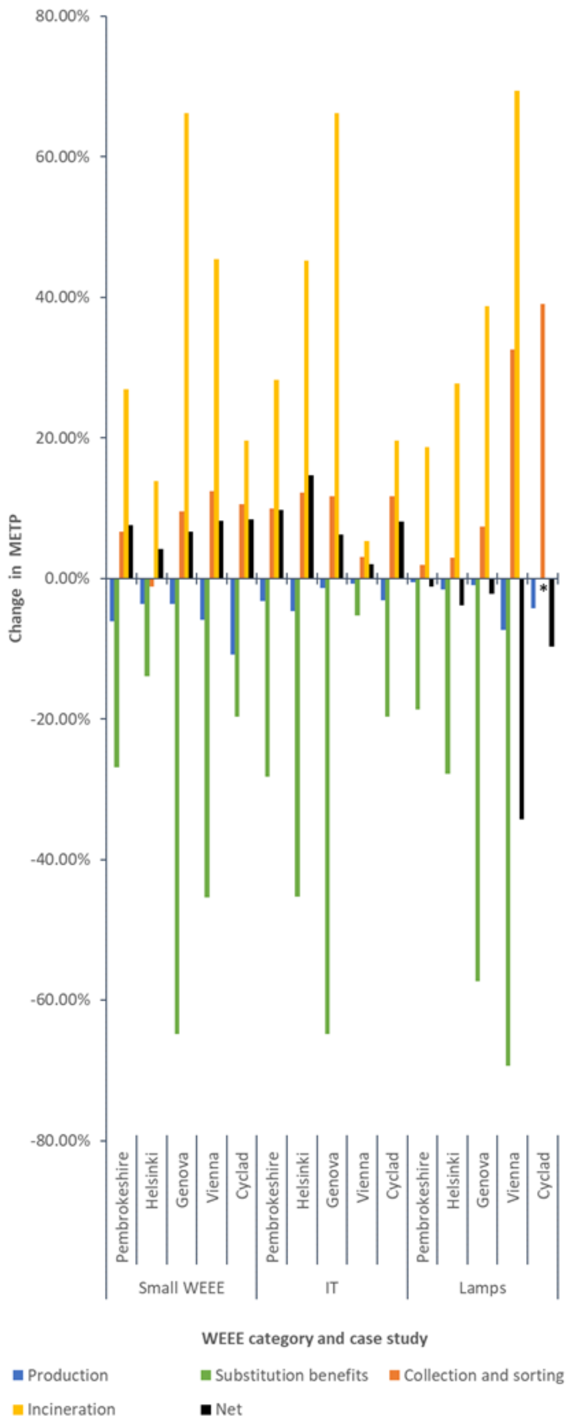

Figure 35: Percentage change in the METP per kg of waste, generated for each WEEE category, between different years for each case study (before and after improvement actions).

3.2.3 Reuse

One complementary flow that is in a higher tier in the waste pyramid than recycling the materials recovered from WEEE is the reuse of electrical and electronic equipment. Some municipalities have organised effective WEEE WCS that incorporate "reuse shops". One notable example where the reuse of electrical and electronic equipment has been implemented is Vienna, where in 2015, 337 tonnes of WEEE entered reuse shops (RepaNet, 2018). Of the WEEE categories considered in this report, small WEEE and IT can be collected for reuse. This can be assumed to require some manual labour in terms of the refurbishment of the devises. Some transport will also be required. The reuse of electrical and electronic equipment will result in avoided impacts associated with the production of new materials, hence the avoided environmental impacts associated with the collection of small WEEE and IT are displayed in Table 6. To be consistent with the scope of the report, these avoided impacts do not include potential avoided impacts associated with device assembly. Data is not available to estimate the impacts related to assembly. With more data on the quantities of each WEEE category collected for reuse by each municipality, the avoided impacts associated with the reuse could be subtracted from the net environmental impacts.

Table 6: The environmental impacts (avoided), associated with the production of the *materials* that go into electrical and electronic equipment, per kg of small WEEE and per kg of IT collected for reuse. (Note that these values do not include the environmental impacts associated with the production of these *products*, i.e. household appliances and IT equipment. The avoided impacts from reuse are, therefore, likely much higher (especially for complex IT equipment), but this was not assessed in this report.)

	GWP (kg CO2-eq.)	FDP (kg oil-eq.)	FEP (kg P-eq.)	MEP (kg N-eq.)	TAP (kg SO2-eq.)	METP (1,4-DCB-eq.)
Small WEEE	-3.31	-1.26	-0.0047	-0.039	-0.021	-0.17
IT	-5.03	-1.55	-0.0039	-0.015	-0.030	-0.14

The values provided in Table 6 may be a good indication for relatively simple electrical and electronic equipment (small WEEE, i.e. household appliances such as a toaster), while it is most likely not a good approximation for IT equipment, such as laptops or mobile phones, where much of the environmental impacts are generated during the complex manufacturing processes.

3.2.4 Sensitivity analysis

The sensitivity analysis is performed for each case study for the WEEE capture rate and sorting efficiency, by increasing each of these by 10%. While this is a theoretical analysis, the intention is to indicate at which lifecycle stage measures could be most effective, e.g. investing more into the collection infrastructure or improving the sorting efficiency of sorting facilities. The effects on the total environmental impacts associated each WEEE category, including the production, collection, sorting, recycling and disposal, is shown for each impact category in Table 7 to Table 9. The gross total is also displayed for each municipality, which shows the total change in each impact category value that would occur if capture rates and sorting efficiencies were increased by 10% simultaneously. As for PPW, this effect is cumulative, leading potentially to greater environmental reductions than the sum of changes in all the parameters. This is performed on the most recent data available for each municipality as shown in the delta analysis.

Table 7: Sensitivity analysis results for each municipality for **Small WEEE**. Material losses are reduced by 10% individually at the collection and sorting stages of the lifecycle. The gross total is where both the capture losses and sorting losses are reduced by 10%.

Parameter	Case study	GWP	FDP	FEP	MEP	TAP	METP
Capture loss	Pembrokeshire	-1.12%	-2.38%	-4.18%	-0.28%	-2.15%	3.31%
	Helsinki	-1.19%	-2.37%	-4.30%	-0.29%	-2.12%	3.33%
	Genova	-0.32%	-0.71%	-1.19%	-0.10%	-0.58%	1.54%
	Vienna	-1.06%	-1.93%	-3.87%	-0.25%	-1.78%	2.79%
	Cyclad	-1.47%	-4.45%	-10.62%	-0.48%	-3.84%	4.66%
Sorting loss	Pembrokeshire	-2.30%	-1.54%	-3.98%	-0.26%	-1.66%	-14.07%
	Helsinki	-2.33%	-1.59%	-4.07%	-0.26%	-1.72%	-14.24%
	Genova	-0.82%	-0.51%	-1.17%	-0.10%	-0.59%	-6.55%
	Vienna	-1.55%	-1.00%	-2.39%	-0.18%	-1.09%	-11.50%
	Cyclad	-4.64%	-3.56%	-10.74%	-0.50%	-3.74%	-20.07%
Gross total	**Pembrokeshire**	**-3.66%**	**-4.08%**	**-8.56%**	**-0.57%**	**-3.98%**	**-12.18%**
	Helsinki	**-3.76%**	**-4.13%**	**-8.78%**	**-0.58%**	**-4.01%**	**-12.33%**
	Genova	**-1.22%**	**-1.28%**	**-2.47%**	**-0.20%**	**-1.23%**	**-5.66%**
	Vienna	**-2.78%**	**-3.05%**	**-6.54%**	**-0.44%**	**-2.99%**	**-10.04%**
	Cyclad	**-6.57%**	**-8.36%**	**-22.41%**	**-1.02%**	**-7.95%**	**-17.39%**

Table 8: Sensitivity analysis results for each municipality for IT. Material losses are reduced by 10% individually at the collection and sorting stages of the lifecycle. The gross total is where both the capture losses and sorting losses are reduced by 10%.

Parameter	Case study	GWP	FDP	FEP	MEP	TAP	METP
Capture loss	Pembrokeshire	-0.58%	-1.70%	-2.31%	-0.63%	-1.36%	4.04%
	Helsinki	-0.61%	-1.77%	-2.41%	-0.65%	-1.40%	4.12%
	Genova	-0.14%	-0.39%	-0.51%	-0.15%	-0.31%	1.50%
	Vienna	-0.61%	-1.75%	-2.53%	-0.65%	-1.40%	4.03%
	Cyclad	-0.65%	-2.09%	-2.95%	-0.76%	-1.66%	4.50%
Sorting loss	Pembrokeshire	-1.65%	-1.41%	-2.22%	-0.56%	-1.19%	-21.09%
	Helsinki	-1.70%	-1.49%	-2.31%	-0.58%	-1.25%	-21.52%
	Genova	-0.41%	-0.33%	-0.48%	-0.14%	-0.29%	-7.66%
	Vienna	-1.64%	-1.41%	-2.07%	-0.56%	-1.19%	-21.65%
	Cyclad	-2.15%	-1.91%	-2.95%	-0.73%	-1.59%	-23.83%
Gross total	**Pembrokeshire**	**-2.39%**	**-3.26%**	**-4.76%**	**-1.25%**	**-2.67%**	**-19.16%**
	Helsinki	**-2.48%**	**-3.40%**	**-4.96%**	**-1.29%**	**-2.78%**	**-19.55%**
	Genova	**-0.59%**	**-0.75%**	**-1.04%**	**-0.31%**	**-0.63%**	**-6.94%**
	Vienna	**-2.42%**	**-3.31%**	**-4.81%**	**-1.26%**	**-2.71%**	**-19.79%**
	Cyclad	**-3.02%**	**-4.19%**	**-6.19%**	**-1.56%**	**-3.41%**	**-21.68%**

Table 9: Sensitivity analysis results for each municipality for lamps. Material losses are reduced by 10% individually at the collection and sorting stages of the lifecycle. The gross total is where both the capture losses and sorting losses are reduced by 10%.

Parameter	Case study	GWP	FDP	FEP	MEP	TAP	METP
Capture loss	Pembrokeshire	-0.94%	-0.93%	-1.58%	-1.02%	-1.13%	-0.78%
	Helsinki	-2.25%	-2.21%	-4.11%	-2.47%	-2.77%	-1.83%
	Genova	-0.82%	-0.80%	-1.36%	-0.89%	-0.98%	-0.68%
	Vienna	-7.92%	-7.68%	-23.43%	-9.09%	-10.93%	-12.84%
	Cyclad	-0.99%	-0.97%	-1.70%	-1.08%	-1.20%	-0.82%
Sorting loss	Pembrokeshire	-0.65%	-0.55%	-1.04%	-0.47%	-0.69%	-0.68%
	Helsinki	-1.57%	-1.32%	-2.70%	-1.14%	-1.70%	-1.61%
	Genova	-0.51%	-0.43%	-0.80%	-0.37%	-0.54%	-0.54%
	Vienna	-5.49%	-4.57%	-15.31%	-4.17%	-6.67%	-11.39%
	Cyclad	-0.90%	-0.76%	-1.47%	-0.65%	-0.96%	-0.94%
Gross total	**Pembrokeshire**	**-1.66%**	**-1.53%**	**-2.72%**	**-1.54%**	**-1.89%**	**-1.54%**
	Helsinki	**-3.97%**	**-3.66%**	**-7.08%**	**-3.72%**	**-4.64%**	**-3.60%**
	Genova	**-1.38%**	**-1.28%**	**-2.24%**	**-1.29%**	**-1.58%**	**-1.28%**
	Vienna	**-13.96%**	**-12.71%**	**-40.29%**	**-13.69%**	**-18.27%**	**-25.38%**
	Cyclad	**-1.96%**	**-1.79%**	**-3.28%**	**-1.78%**	**-2.23%**	**-1.83%**

For most impact categories, the reduction in WEEE capture losses results in reduced environmental impacts. The only exception to this is the METP, which increases with reduced capture losses in the small WEEE and IT. This is due to the increased amounts of metal that is processed within the scope of the analysis when more WEEE is collected (Table 7 and Table 8). On the other hand, reduced sorting losses results in more of the collected metal being recycled, so METP is reduced. The greatest reductions in environmental impacts in most impact categories is for lamps. This is due to the materials that lamps are made of being easier to process and ultimately recycle. Since lamps make up the smallest portion of WEEE out of the three categories, even in municipalities where capture rates are relatively high, the relative environmental impacts that can be avoided by reducing capture losses of lamps are small.

The sensitivity analysis reveals the change in each environmental impact category that might be expected following a reduction in different material losses. In terms of GWP, larger reductions are achieved when sorting losses are reduced for small WEEE and IT, compared to reducing capture losses (Table 7 and Table 8). This is related to the incineration of the material lost while sorting. For all other impact categories, except MEPT, reducing capture losses of small WEEE and IT had larger environmental benefits than reducing sorting losses. However, improving the capture rate of lamps is more important than improving the sorting efficiencies for every environmental impact category (Table 9). Recycling losses are not considered for WEEE, however the recycling of the materials in WEEE is limited and requires substantial improvement in the pursuit of closing the loops in a circular economy.

A larger change in the environmental impact values is achieved in the sensitivity analysis by municipalities that had lower capture losses already. Differences in the relationship between the environmental impact and the reduction in capture losses for each category can be attributed to differences in the collection efficiency between municipalities.

3.2.5 Discussion

Despite WEEE addressing regulations, only one third of electrical and electronic waste in the European Union is reported as separately collected and appropriately treated. This implies that two thirds still go to landfills or to sub- standard treatment sites. WEEE is a complex mixture of materials and components that if not properly managed can cause major environmental and health problems. Moreover, the production of modern electronics relies on scarce and expensive resources (e.g. around 10% of total gold worldwide is used for their production) and such material loops need to be closed as much as possible within a circular economy. At the same time WEEE is source of other valuable materials, such as ferrous metal, non-ferrous metal and plastics which could be recovered if both collection and processing efficiencies are improved.

There is a large knowledge gap when it comes to WEEE, which makes modelling the system holistically and accurately from a lifecycle perspective difficult. Of the 5 case studies, 72% of the waste that is not collected has an unknown fate. This WEEE may be simply being stored by the consumer for many years (“hibernating”), or it may be being exported to a different country where valuable parts may be salvaged before the rest of the material is incinerated. The material that ends up in residual waste is accounted for in the material flow analysis, but like the material that has an unknown fate this is also left out of the scope of the LCA. This is because the ultimate treatment of this WEEE is not clear. It is also unclear how WEEE may be treated in complementary flows; this too is left out of the analysis. Based on the quantities of material unaccounted for by the LCA, the missing environmental impact values may be considerable. For instance, if most of the WEEE is exported and incinerated, the environmental impacts may be quite large. However, if the WEEE is mostly hibernating, the environmental impacts are negligible (Bertram, et al., 2002). If some of the material in the complementary flows is recycled, this may contribute to additional avoided impact. The system boundary of the LCA methodology presented here could be expanded to incorporate these extra material flows, yet this requires data to become available on the fate and processing of these flows.

A large proportion of the material found in the WEEE waste stream is plastic. However, in order to capture this material effectively as part of a circular economy, there is need for a greater knowledge of WEEE plastics, justified by the need to evaluate their recyclability in such a way that could promote better WEEE dismantling strategies and improve plastics recovery (Martinho, et al., 2012). Flame retardants reduce the material melting point, making mechanical and other recycling treatment of plastic difficult. Flame retardants also raise environmental concerns that limit the recovery of plastic, because they are almost entirely prohibited in incineration plants. The identification of polymers can be an issue at the sorting stage. Furthermore, the use of several different types of polymer in a single type of equipment and the combination of plastics and metal, contaminates both waste types. Of the small WEEE and IT, in which plastic makes up 42% and 40% of the material by mass respectively, plastic is on average responsible for 71% and 72% of the greenhouse gas emissions associated with these categories respectively in the 5 case studies.

As with plastic packaging waste, the post collection material recovery (i.e. the sorting stage) is the most important stage to improve for small WEEE and IT in terms of reducing greenhouse gas emissions. It is also the most important stage with regards to METP, as this impact is dependent upon the treatment of the metals contained in the WEEE. For lamps, improvements to the capture rate had the most relative impact on every impact category.

As for the PPW, the use phase of the WEEE is not considered. However, unlike the PPW, the WEEE categories are likely to have considerable environmental impacts associated with the use phase, since these products require energy inputs throughout this phase. Although beyond the scope of this research, designing energy efficient devices is important from a circular economy perspective. This can be improved via advancements in product design. Likewise, improved material design may improve sorting efficiencies, and thus WEEE recycling, in the future. Many of the materials in WEEE simply cannot be recycled due the complexity of their components. Better product design should consider the recyclability of all the materials in the products.

3.3 Construction and Demolition Waste

3.3.1 Environmental impacts

The environmental impact assessment results for CDW show the environmental impact values associated with the production, collection, recycling and disposal, as well as the substitution of primary materials of 1 kg of each material included in the study: bricks, insulation, sanitary ceramics and gypsum. The impacts associated with transporting the waste for recycling, the recycling process and the disposal of the non-recyclable portions of the waste contribute to the impacts. The avoided primary production of material and the avoided disposal contribute to the avoided impacts of each waste material.

3.3.1.1 Odense – bricks

For all impact categories, it can be observed that a substantial impact reduction can be achieved by reusing the (undamaged) bricks (shown by "avoided primary production, bricks" in Figure 36 to Figure 41, where the dot represents the net impact including substitution). All other activities, including collection and sorting, recycling and disposal, as well as transportation are of minor importance only. This means that also the recycling of bricks for road material yields only minor benefits, which can be explained by the fact that it replaces gravel, which is a relatively low-impact material.

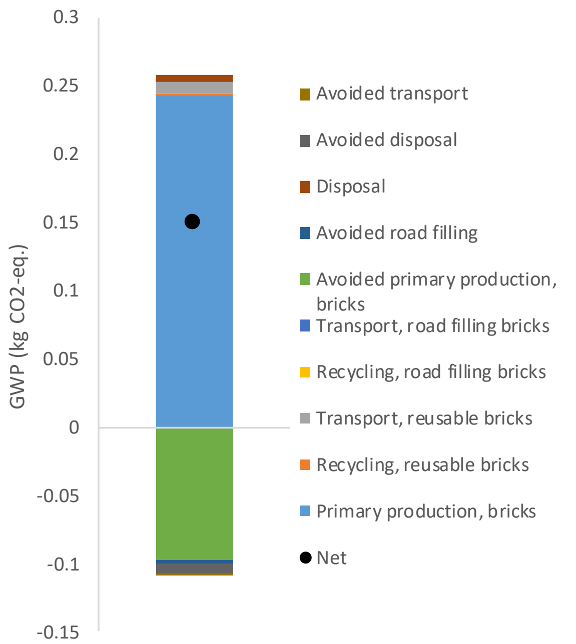

Figure 36: Global warming potential (GWP; kg CO_2-eq.) per kg of waste bricks generated.

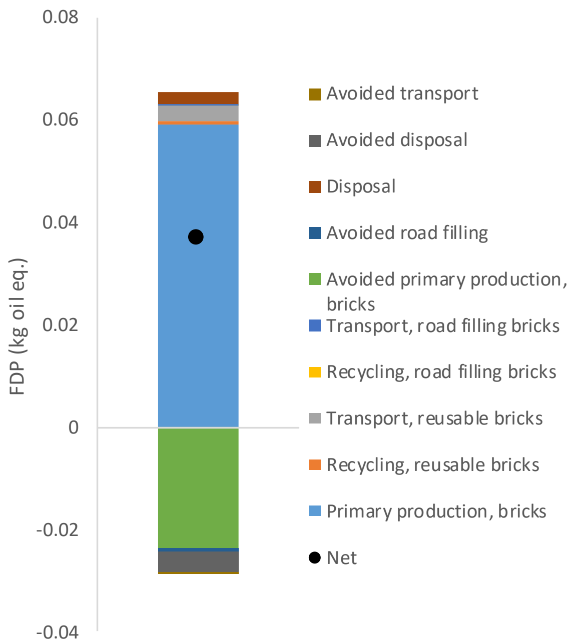

Figure 37: Fossil depletion potential (FDP), calculated as the equivalent energy based on the upper heating value of crude oil, (42 MJ per kg, in ground) per kg of waste bricks generated.

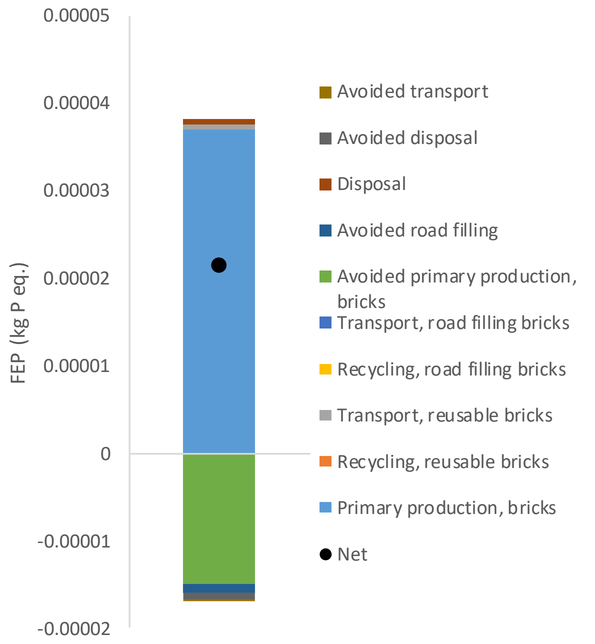

Figure 38: Freshwater eutrophication potential (FEP; kg P-eq.) per kg of waste bricks generated.

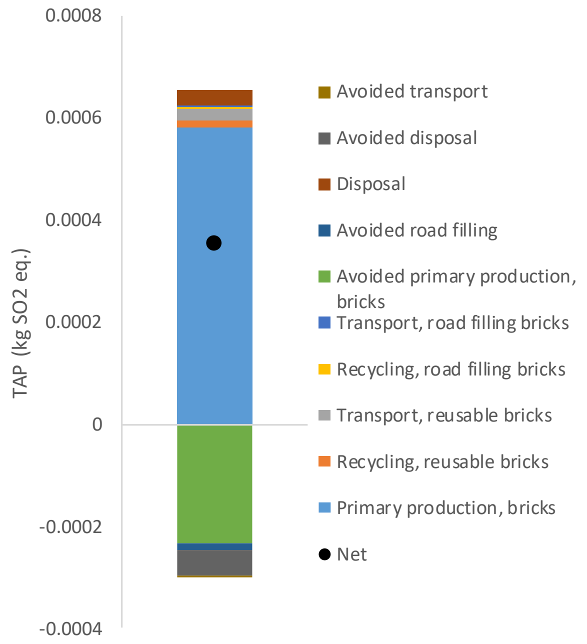

Figure 40: Terrestrial acidification potential (TAP; kg SO_2-eq.) per kg of waste bricks generated.

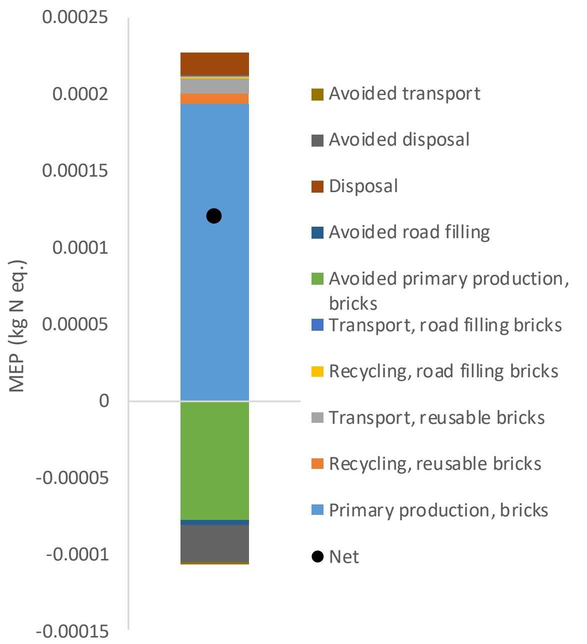

Figure 39: Marine eutrophication potential (MEP; kg N-eq.) per kg of waste bricks generated.

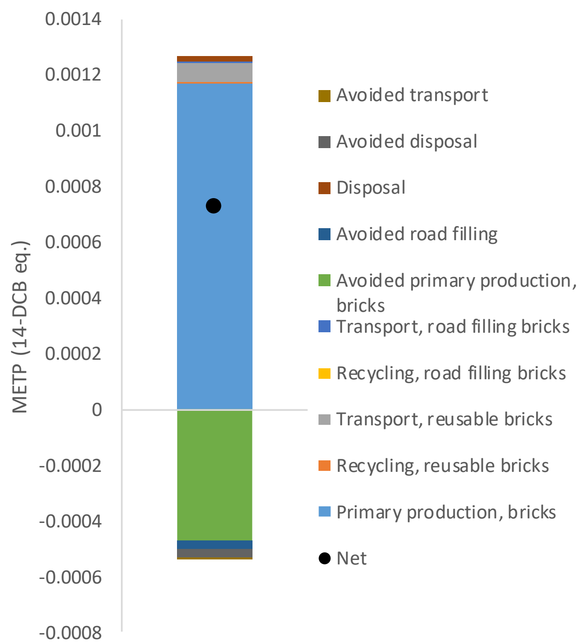

Figure 41: Marine ecotoxicity potential (METP; 1,4 dichlorobenzenes-eq.) per kg of waste bricks generated.

3.3.1.2 Odense – insulation

For insulation material, the substitution of virgin through recycled insulation material yields high environmental benefits across all impact categories (Figure 42 to Figure 47). The only other activity that consistently contributes to environmental impacts is the recycling process for insulation materials due to its energy and water consumption.

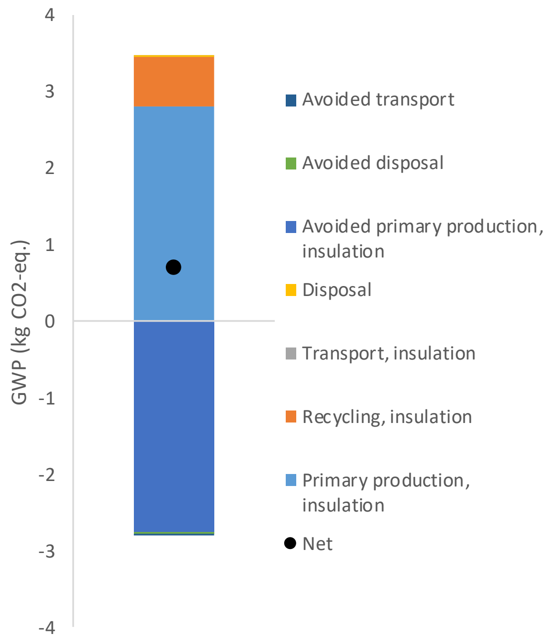

Figure 42: Global warming potential (GWP; kg CO_2-eq.) per kg of waste insulation generated.

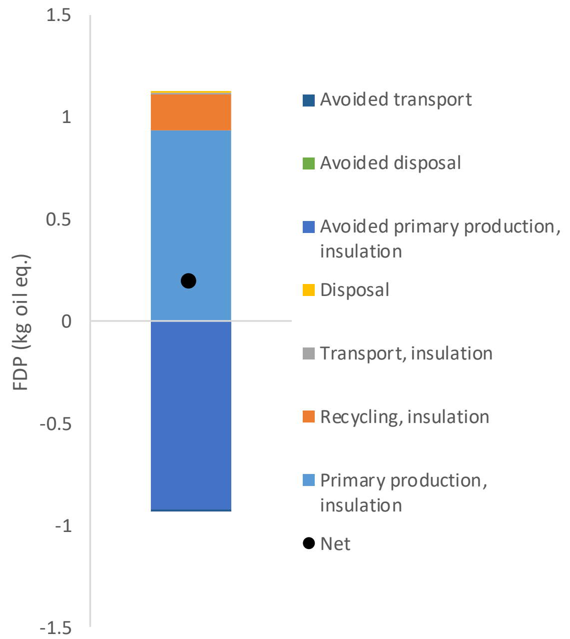

Figure 43: Fossil depletion potential (FDP), calculated as the equivalent energy based on the upper heating value of crude oil, (42 MJ per kg, in ground) per kg of waste insulation generated.

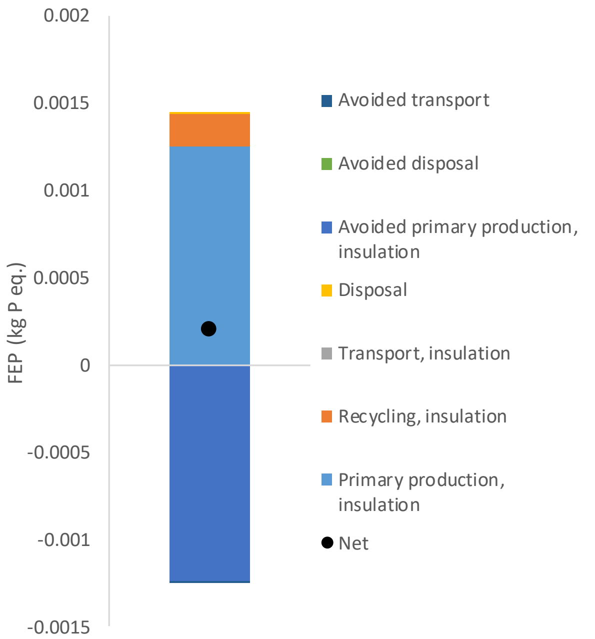

Figure 44: Freshwater eutrophication potential (FEP; kg P-eq.) per kg of waste insulation generated.

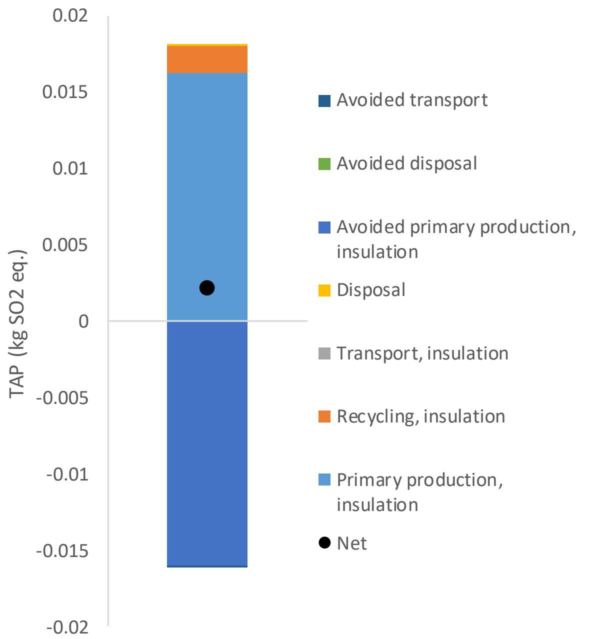

Figure 46: Terrestrial acidification potential (TAP; kg SO_2-eq.) per kg of waste insulation generated.

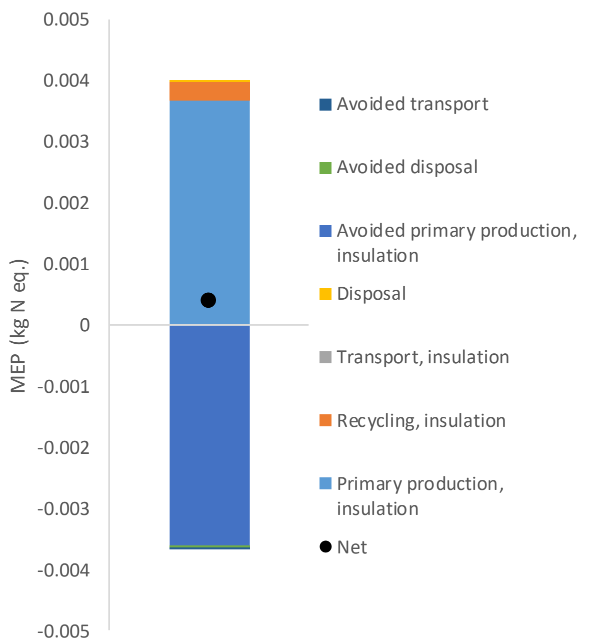

Figure 45: Marine eutrophication potential (MEP; kg N-eq.) per kg of waste insulation generated.

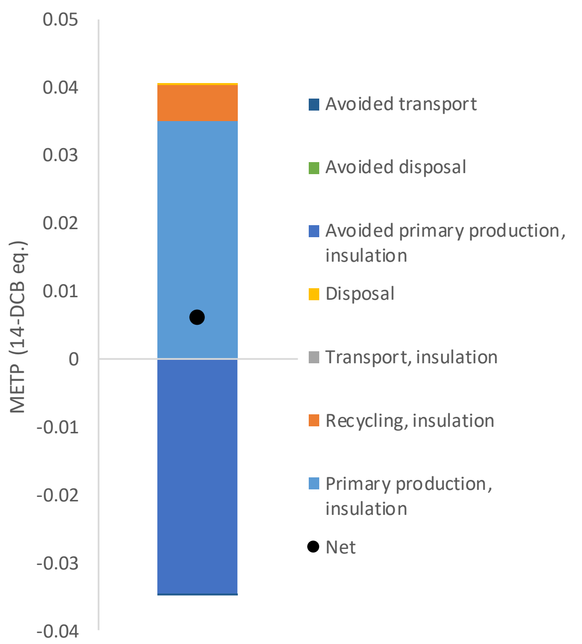

Figure 47: Marine ecotoxicity potential (METP; 1,4 dichlorobenzenes-eq.) per kg of waste insulation generated.

3.3.1.3 Odense – sanitary ceramics

The environmental benefits of recycling sanitary ceramics in concrete are, although existent, very small compared to the production of ceramics (Figure 48 to Figure 53). This is mainly due to the fact that disposed of sanitary ceramics are not used to displace primary sanitary ceramics, but are instead used to replace sand and gravel in concrete, which is associated low environmental compared to the production of sanitary ceramics. The highest environmental gain is to be identified for marine eutrophication (MEP), which is due to the avoided production of aggregates and the avoided disposal of the sanitary ceramics. Naturally, the benefits associated with the recycling of sanitary ceramics are reduced with increasing transportation distance. For METP this distance is as low as 135 km (as of then, recycling would actually lead to increased METP).

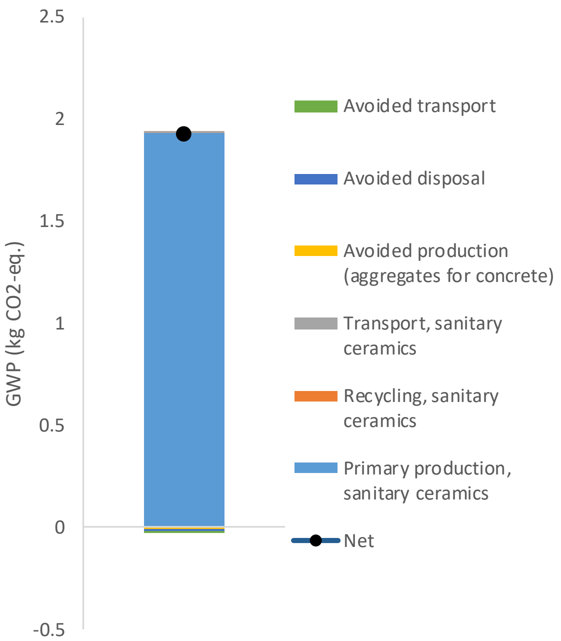

Figure 48: Global warming potential (GWP; kg CO_2-eq.) per kg of waste sanitary ceramics generated.

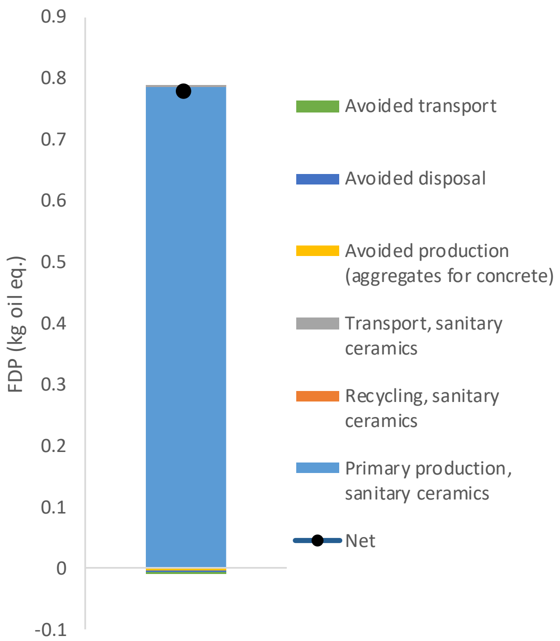

Figure 49: Fossil depletion potential (FDP), calculated as the equivalent energy based on the upper heating value of crude oil, (42 MJ per kg, in ground) per kg of waste sanitary ceramics generated.

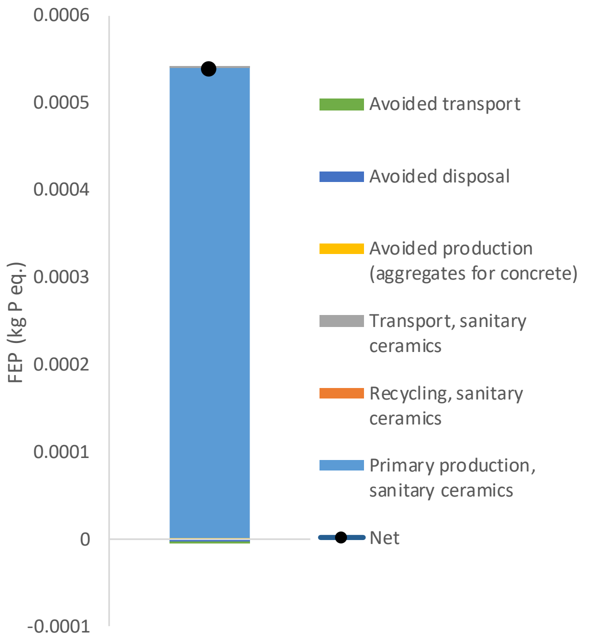

Figure 50: Freshwater eutrophication potential (FEP; kg P-eq.) per kg of waste sanitary ceramics generated.

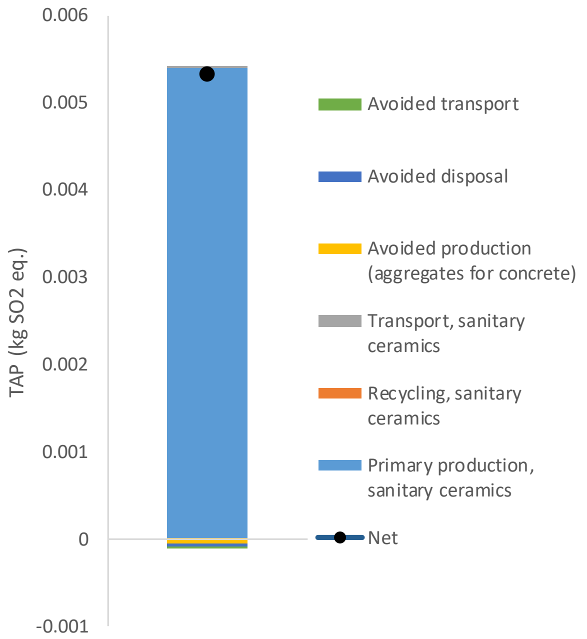

Figure 52: Terrestrial acidification potential (TAP; kg SO_2-eq.) per kg of waste sanitary ceramics generated.

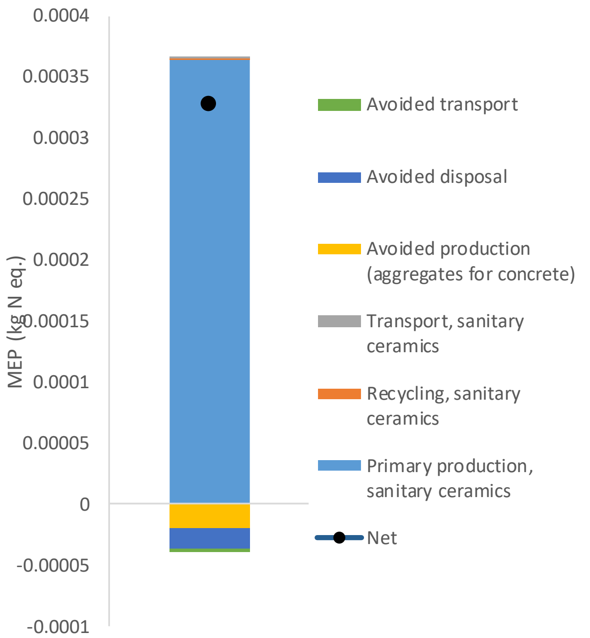

Figure 51: Marine eutrophication potential (MEP; kg N-eq.) per kg of waste sanitary ceramics generated.

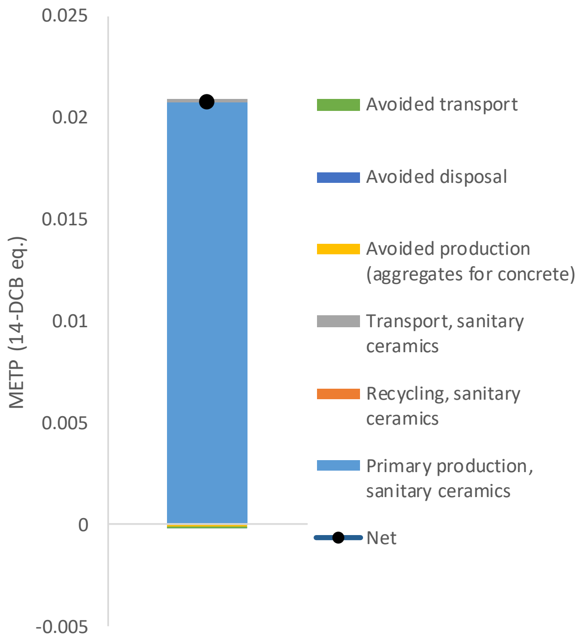

Figure 53: Marine ecotoxicity potential (METP; 1,4 dichlorobenzenes-eq.) per kg of waste sanitary ceramics generated.

3.3.1.4 Reimerswaal – gypsum

Recycling gypsum yields considerable environmental benefits for all impact categories analysed (Figure 54 to Figure 59). However, recycling gypsum is also associated with notable environmental impacts, mainly due to the energy requirements in the recycling process. For terrestrial acidification (TAP, Figure 58), the avoided disposal contributes the most to the environmental impact of gypsum. For all other environmental impact categories, the avoided impacts associated with primary production contributes to the most environmental benefits of recycling gypsum.

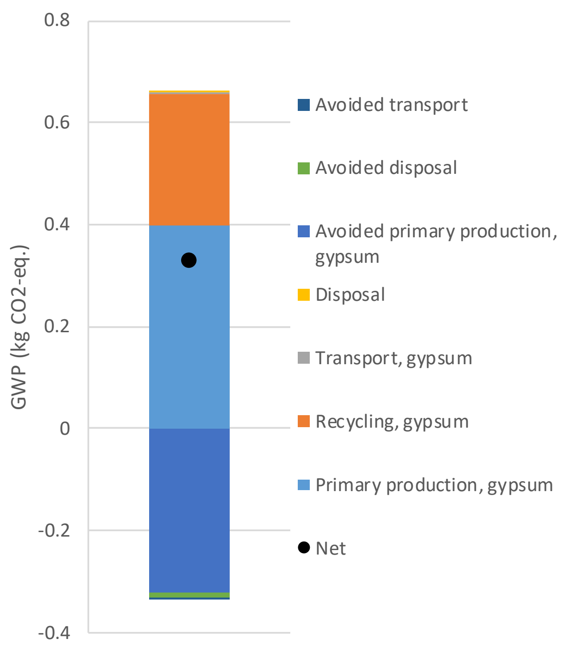

Figure 54: Global warming potential (GWP; kg CO_2-eq.) per kg of waste gypsum generated.

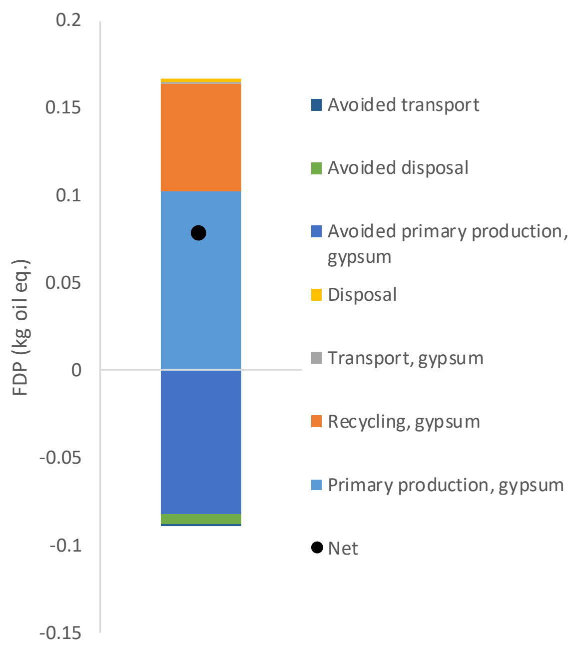

Figure 55: Fossil depletion potential (FDP), calculated as the equivalent energy based on the upper heating value of crude oil, (42 MJ per kg, in ground) per kg of waste gypsum generated.

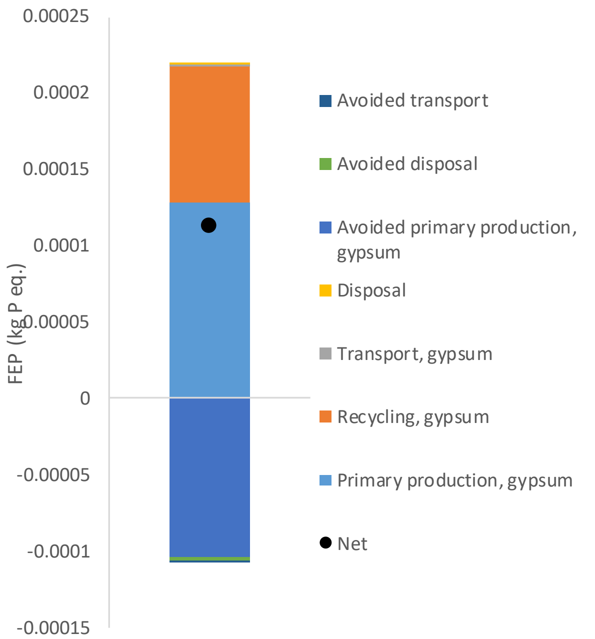

Figure 56: Freshwater eutrophication potential (FEP; kg P-eq.) per kg of waste gypsum generated.

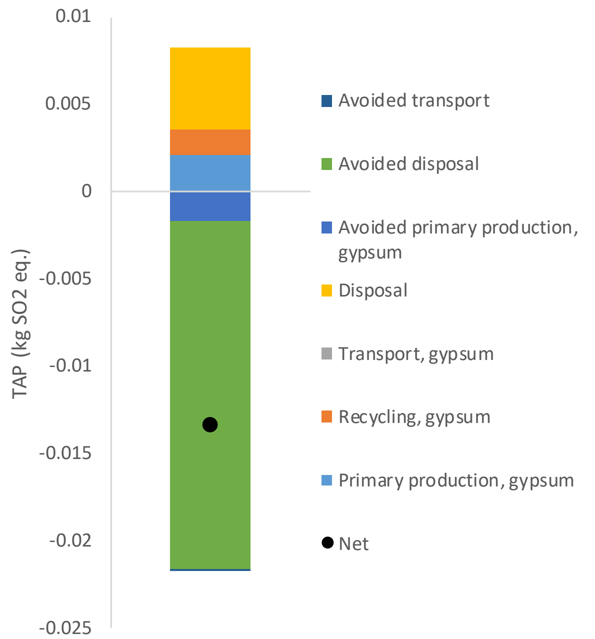

Figure 58: Terrestrial acidification potential (TAP; kg SO2-eq.) per kg of waste sanitary ceramics generated.

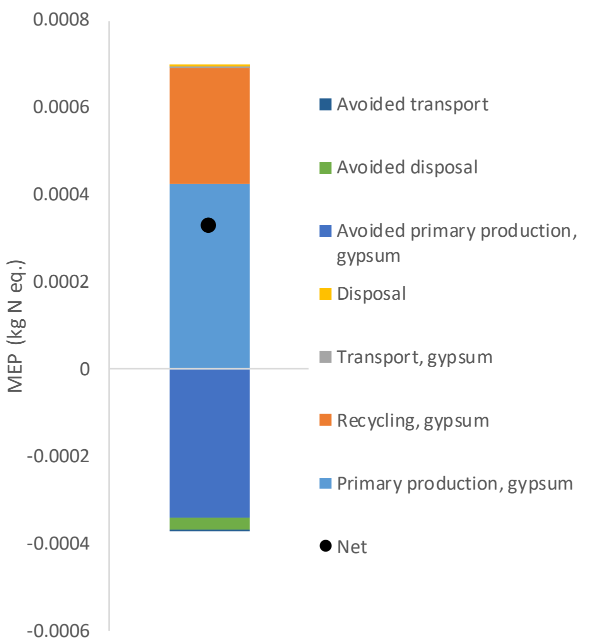

Figure 57: Marine eutrophication potential (MEP; kg N-eq.) per kg of waste gypsum generated.

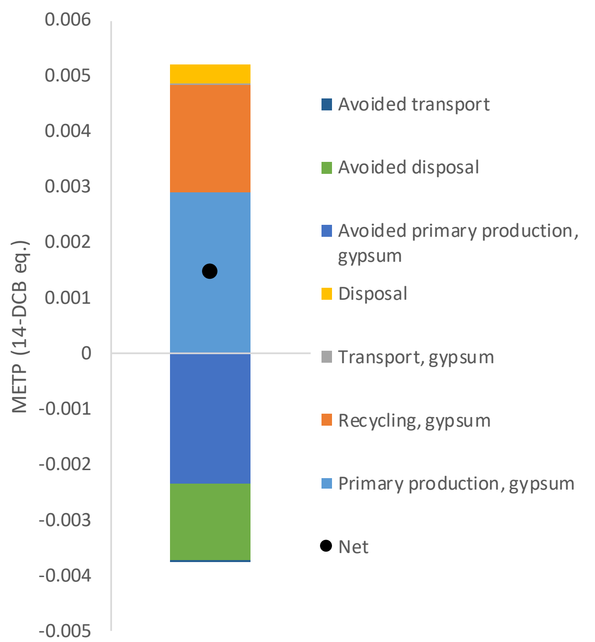

Figure 59: Marine ecotoxicity potential (METP; 1,4 dichlorobenzenes-eq.) per kg of waste sanitary ceramics generated.

3.3.2 Discussion

CDW is one of the heaviest and most voluminous waste streams generated in the EU and as such it has been identified as a priority waste stream by the European Union. It accounts for approximately 25% - 30% of all waste generated in the EU and consists of numerous materials, including concrete, bricks, gypsum, wood, glass, ceramics, metals, plastic, solvents, asbestos and excavated soil, many of which can be recycled. Here, the focus is on two systems which manage well the waste bricks, insulation, sanitary ceramics and gypsum produced by the municipalities. The associated environmental impacts and benefits with each material and its associated waste treatment are assessed, so that the net environmental impact can be calculated.

CDW arises from activities such as the construction of buildings and civil infrastructure, total or partial demolition of buildings and civil infrastructure, road planning and maintenance (European Commission, 2019). Technology for the separation and recovery of construction and demolition waste is well established, readily accessible and in general inexpensive. Despite this, and despite its potential, the level of recycling and material recovery of CDW varies greatly (between less than 10% and over 90%) across the European Union. If not separated at source, CDW can contain hazardous waste, the mixture of which can pose particular risks to the environment and can hamper recycling. A minimum of 70% (by weight) of non-hazardous construction and demolition waste (excluding uncontaminated soils and naturally occurring material) shall be prepared for reuse, recycled or undergo other material recovery, such as backfilling operations using waste to substitute other materials (European Commission, 2008).

Of the CDW materials assessed as part of the COLLECTORS project, two had secondary material flows that replaced a primary production of aggregate: for waste bricks, material that is not suitable for reuse as bricks is crushed for use in road filling, meanwhile sanitary ceramics can be crushed to be used in concrete. One of the natural ways of reusing inorganic industrial wastes, is their use in the production of building materials, especially as raw materials in the concrete manufacture (Halicka, et al., 2013). This manner of recycling has positive impact on the environment; reducing the amount of deposited waste and limiting the mining of mineral aggregate deposits. Inorganic ceramic waste has an additional advantage – it needs no special processing when used as an aggregate; for instance, the technology of producing the concrete mix with aggregate using recycled sanitary ceramics is the same as it is in the production of concrete mix with traditional aggregate. However, as can be seen in the results of this report, the environmental benefits to be gained via the replacement of conventional aggregate materials are considerably lower than reducing the need for other materials. For instance, reusing waste bricks in new buildings as bricks results in much higher environmental savings. Environmental benefits related to the reuse of bricks could be further increased, if the capture rate and the proportion of undamaged bricks could further be increased.

In the case of insulation materials and gypsum, important environmental benefits are associated with a closed-loop recycling of these materials. However, these are partially offset by the additional energy and material inputs required during the recycling processes (this is strongly related to the environmental impacts of the energy mix and thus in the future, with an increased share of renewables, we expect the impact linked to the recycling processes to decrease). Transport is also an important source of environmental impacts when managing CDW wastes due to their weight, particularly compared to PPW and WEEE. Thus, while we find that there are generally rather large environmental benefits associated with the reuse and recycling of CDW, it is important to 1) identify the best options for reuse and recycling using an LCA approach (preferring reuse whenever possible and considering in parallel economic and social drivers), and 2) balancing the optimal reuse and recycling options with transport as to not transport the material too far.

4 Conclusions

4.1 Assessment method

The aim of this study is to assess the environmental performance of different waste collection systems for PPW, WEEE and CDW in Europe and to quantify the resource recovery potential and associated environmental benefits of each WCS, building upon a general methodology developed in D3.1 of the COLLECTORS project. This methodology extends the system boundaries from that of the WCS to include production, recycling, and disposal using data from literature and databases whenever local data is not available. This allows the practitioner to identify the consequences of decisions at the WCS and can point to where changes along the life cycle of the modelled materials and their waste management will show the largest environmental impact improvements. Thus, carrying out an LCA on waste management systems, as has been performed in this report, can show how and where to act to improve the circularity of materials whilst reducing environmental impacts. The case studies selected and presented in this report represent good examples of waste collection, and although each municipality has unique characteristics some general conclusions can be drawn and are given in the following.

4.2 Environmental improvements through waste management

Can better collection and waste management really substantially reduce environmental impacts associated with materials used for paper and packaging, electronic goods and construction? The simple answer is - yes, it can. There is a substantial potential to reduce the environmental impacts for all materials covered in this report through a better management of waste streams.

Efficiency

In general, we observed that recycling materials in a closed-loop, i.e. back into the original material streams (e.g. metals, plastics, and bricks) yields high environmental benefits. The key to this is efficiency along the waste management chain, i.e. high capture rates, as well as high sorting and recycling efficiencies. Down-cycling of, e.g. plastics or sanitary ceramics, also yield environmental benefits, although typically lower than replacing the original material. Thus, whenever possible high value recycling options should be explored first, but if not available, down-cycling still yields environmental benefits to some extent.

Increasing capture rates

Across all waste streams, increasing the capture rates had the largest effect on the environmental impact reductions. In general, it was found that the collection stage itself had relatively low associated impacts when compared to the whole life cycle of the materials. This suggests that if a municipality were to make additional investments into its collection scheme in order to achieve reduced capture and sorting losses, and thereby increase the environmental impacts associated with these, this would likely result in lower overall environmental impacts when looked at holistically from a life cycle perspective. This was shown in our delta analysis for WEEE, where net environmental impact reductions were achieved in every case study even where the impacts associated with collection and sorting increased.

Collection method

The COLLECTORS database revealed that there are differences in the capture rate associated with different implementations of waste collection schemes (COLLECTORS, 2019). For example, the PMD + Fibres commingling method seemed to yield lower capture rates (for reasons that we cannot fully explain, see also the discussion in section 3.1.4). While we do not believe in a one-shoe-fits-all solution, municipalities across Europe should continue to learn from each other's success stories and best practices in implementing collection schemes that maximize capture rates.

The importance of quality

Although the capture rate was generally the single most important factor for environmental benefits, other factors were more important for certain waste streams. For plastics, for example, the greatest total reductions in the environmental impacts resulted from decreasing the sorting and recycling losses. This is largely due to contamination and thus the waste not being able to meet the quality requirements for a recycling within the original grade of plastics (down-cycling). Thus, for plastics, the main effort should be on improving the purity and qualities of the waste fractions obtained after collection and sorting and then ensuring that these materials are recycled in higher value applications.

Energy recovery

While energy recovery is environmentally beneficial in situations where material recovery is too difficult, our analysis also showed that the incineration of paper and plastic remains a relatively good option from an environmental perspective in some municipalities (e.g. Berlin). While this is may be true for the current situation where a relatively high-impact energy mix is displaced, we expect that this situation will change as the share of renewables in the energy mix keeps growing.

Transport

Transportation seems to play a minor role from the environmental perspective in the management of waste. It only really becomes a critical factor for heavy wastes, such as CDW, if these need to be transported over longer distances. In situations where the recycling yields only minor benefits, e.g. for sanitary ceramics which are crushed and used as road filling material (thus replacing sand or gravel), the additional impact of transportation should be considered in the analysis.

Reuse

Although reuse was not a focus of this report, our analyses show (e.g. for IT equipment and bricks) that reuse has a very high environmental potential and thus the opportunities for reusing “waste materials” should be explored whenever possible as they may be preferable to recycling. Our findings here are in line with the well-known waste hierarchy (prevent, minimize, reuse, recycle, recover energy, and dispose).

Holistic perspective on materials use

Although we have not investigated the following solutions in our report, we would like to point out a number of other important ways of improving the management of waste throughout Europe. This starts at the product design stage, where increasing attention should be given to design for recycling (e.g. for the upcoming end-of-life batteries that can be expected with an increasing number of electric vehicles on the roads). This includes better packaging design, whereby packaging is made out of more recyclable materials. And finally, the post collection recovery efficiency can be further improved through better management and technological advancements at the sorting and recycling stages. This may require the use of novel technologies such as replacing mechanical recycling with chemical recycling to maximise the life time of materials (Rahimi & García, 2017). The recycling of valuable materials can also be increased by recovering resources from residual waste streams before they reach incineration or landfills.

Towards circularity

All of these measures together have the potential to make a big contribution to closing material loops and moving towards a circular economy with lower the environmental impact of the products we consume. At the same time, we have a long way to go for certain materials (e.g. plastics). Meanwhile, taking the first element of the waste hierarchy seriously, i.e. producing less waste, is without doubt the most environmentally sustainable solution. The literature on the topic of the circular economy has many interesting approaches to offer to make this happen, including, amongst others, the design of long-lasting products, that can be reused, repaired, and eventually easily recycled and alternative business models that facilitate a smart use of resources, such as sharing or service models.

4.3 Future research needs

Best practices for collection

Within the COLLECTORS database and in between the case studies of this report, we have large differences in the capture rate for the same waste streams (COLLECTORS, 2019). More data and understanding is required as to the underlying factors in order to systematically improve waste collection throughout Europe. While there may not be the single best solution that fits everywhere, there is a large potential that municipalities can learn from each other. In the COLLECTORS data it was also observed that municipalities which employ PMD + Fibres commingling have lower capture rates for every PPW material on average, as discussed in section 3.1.4. This might simply reflect national collection trends, as a significant country effect can be observed in the data; the majority of the municipalities which employ PMD + Fibres commingling within the COLLECTORS database are in the UK and France (COLLECTORS, 2019). A possible explanation for these lower capture rates also may lie in the behaviour of citizens. To better understand the technical and social factors that drive these systems, more research is needed.

High quality recycling

For all waste streams covered in this report, the quality of waste materials after collection was a key factors deciding on their fate and consequently the circularity and environmental impact reductions that waste management systems can offer. In the case of plastics, for example, the biggest limitation seems currently not to be the collection of plastics, but low recycling rates due to contaminations and other quality related factors (Eriksen, et al., 2018). This applies also for WEEE plastics, which are often a combination of polymers and metals, leading to the contamination of both waste streams. Further research and practical tests are needed in order to find solutions to perform high quality recycling. Energy recovery is in this case only an intermediate solution as long as the share of renewables in the energy mixes is small (although obviously also in the future the recovery of energy from wastes that cannot be further recycled is environmentally meaningful). Obviously, the potential of high quality recycling is already defined to some extent at the product design stage and later depends on the behaviour of consumers and the waste management system. Thus, increasing high quality recycling requires a holistic perspective on how we manage our resources and the involvement of all stakeholders along the lifecycle of these products.

Better data

In this report we try to provide a holistic perspective on the management of materials and their management in three waste streams (PPW, WEEE and CDW). This was only possible due to the availability of European statistics, national and municipality reports and lifecycle databases such as ecoinvent. As stated previously, not all of this data reflects the actual value chains and processing steps for the municipalities investigated. Instead, a substantial amount of “average” data is used to be able to keep a holistic perspective while still trying to model the consequences of collection at a given municipality. While there is a certain advantage to this, which is that in this way the comparability across municipalities can be facilitated (with only collection and sorting being modelled from local data and most of the other data reflecting the average European situation), there is also the disadvantage, that the recommendations for specific municipalities are at a more generic level. More local data is thus needed to guide individual municipalities in their efforts to increase capture rates and provide the waste fractions in qualities that enable high value recycling. In fact, municipalities reported that it is often unclear for them 1) which quality requirements should be achieved to ensure high value recycling and 2) how they can implement this.

Better data is also needed to understand the real substitution effects in open-loop recycling. As discussed in section 2.2, most recycled material entering the open-loop recycling is assumed to avoid the production of the same material, of equal quality, from virgin materials. In some cases, entirely different raw materials may be replaced by a recycled material (Suter, et al., 2017). Thus, the impacts associated with open-loop recycling must be regarded as indicative of the potential avoided impacts associated with the collected material only. While we tried to model the actual substitutions whenever possible, better data is needed to improve models like ours in the future.

Finally, better data is needed on complementary flows, i.e. flows that are outside of the proper collection and recycling chains, and for which data is mostly missing. Especially for WEEE these flows are currently larger than the flows within the proper waste management system. Therefore the environmental impact figures presented here are not fully representative of the real situation. Based on the quantities of material unaccounted for by the LCA, the missing environmental impact values may be considerable. For instance, if most of the WEEE is exported and incinerated, the environmental impacts may be quite large. While not all complementary flows are environmentally detrimental per se (WEEE may also be reused abroad for example), more data is needed to assess the fate of these WEEE flows and associated environmental burdens.

Within the COLLECTORS database (COLLECTORS, 2019), a significant country effect was observed, which indicates great opportunity for member states to learn from one another and increase primary resource substitution in Europe.

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Appendix

A. Additional data for all waste streams

Appendix Table A-1: Environmental impacts associated with conventional energy production in each case study.

Energy	Region	GWP (kg CO2-eq.)	FDP (kg oil-eq.)	FEP (kg P-eq.)	MEP (kg N-eq.)	TAP (kg SO2-eq.)	METP (1,4-DCB-eq.)
Electricity (per MJ)	Italy	1.3E-01	3.8E-02	3.3E-05	1.1E-04	1.0E-04	6.9E-04
	Netherlands	1.6E-01	5.4E-02	6.7E-05	7.4E-05	2.9E-04	1.2E-03
	Belgium	6.3E-02	2.2E-02	1.5E-05	4.0E-05	1.5E-04	4.1E-04
	Germany	1.8E-01	4.8E-02	2.4E-04	1.2E-04	6.5E-04	3.6E-03
	France	4.9E-02	1.5E-02	1.4E-05	7.8E-05	2.2E-04	7.5E-04
	UK	2.1E-01	6.2E-02	6.0E-05	1.5E-04	9.0E-04	1.2E-03
	Finland	2.3E-01	5.3E-02	6.5E-05	1.6E-04	7.3E-04	1.6E-03
	Austria	3.1E-01	8.1E-02	3.6E-04	2.4E-04	1.2E-03	5.6E-03
	Denmark	1.2E-01	2.9E-02	4.1E-05	6.6E-05	3.9E-04	1.2E-03
Heat (per MJ)	EU	5.6E-02	2.4E-02	8.5E-07	1.5E-05	3.9E-05	5.6E-05

B. Additional data for PPW

Appendix Table B-1: Environmental impacts of primary production of each material per kg (no substitution of virgin material).

Material	Material type	Substitution rate	GWP (kg CO2-eq.)	FDP (kg oil-eq.)	FEP (kg P-eq.)	MEP (kg N-eq.)	TAP (kg SO2-eq.)	METP (1,4-DCB-eq.)
Paper	Newsprint	0.00	1.47	0.42	1.32E-03	1.67E-03	8.43E-03	2.90E-02
	Other (non-packaging)	0.00	1.23	0.41	5.53E-04	2.10E-03	8.92E-03	1.55E-02
	Graphic paper	0.00	1.55	0.51	9.34E-04	1.72E-03	8.02E-03	2.18E-02
	Paper (packaging)	0.00	1.42	0.48	7.10E-04	2.06E-03	6.91E-03	1.72E-02
	Cardboard	0.00	1.01	0.29	9.20E-04	2.01E-03	1.09E-03	1.24E-02
	Carton board	0.00	0.61	0.18	2.12E-04	7.88E-04	2.60E-03	1.17E-02
Plastic	PS	0.00	4.46	2.36	5.21E-04	3.03E-03	1.49E-02	1.74E-02
	PET	0.00	3.12	1.74	8.42E-04	2.43E-03	1.14E-02	2.55E-02
	HDPE	0.00	2.01	1.73	3.82E-05	1.47E-03	6.39E-03	2.25E-03
	LDPE	0.00	2.81	1.92	3.40E-04	2.30E-03	1.03E-02	9.94E-03

	PP	0.00	2.05	1.71	7.51E-05	1.51E-03	6.12E-03	2.39E-03
Glass	Clear	0.00	1.29	0.38	2.56E-04	1.52E-03	8.29E-03	8.76E-03
	Green	0.00	1.30	0.38	2.56E-04	1.52E-03	8.29E-03	8.77E-03
	Brown	0.00	1.30	0.38	2.56E-04	1.52E-03	8.29E-03	8.77E-03
Metal	Aluminium	0.00	8.14	1.86	4.64E-03	6.91E-03	4.23E-02	2.02E-01
	Steel (Tinplate)	0.00	5.86	1.53	2.32E-03	6.30E-03	3.00E-02	4.31E-01

Appendix Table B-2: Environmental impacts of the closed-loop recycling of each material per kg (virgin material replaced at the substitution rate)

Material	Material type	Substitution rate	GWP (kg CO2-eq.)	FDP (kg oil-eq.)	FEP (kg P-eq.)	MEP (kg N-eq.)	TAP (kg SO2-eq.)	METP (1,4-DCB-eq.)
Paper	Newsprint	0.83	1.11	0.33	8.47E-04	1.17E-03	5.79E-03	1.95E-02
	Other (non-packaging)	0.29	0.63	0.20	2.33E-04	2.19E-03	3.72E-03	8.29E-03
	Graphic paper	0.29	0.79	0.24	5.33E-04	2.25E-03	4.02E-03	1.58E-02
	Paper (packaging)	0.84	0.73	0.26	3.59E-04	1.08E-03	1.89E-03	1.27E-02
	Cardboard	0.84	0.83	0.29	4.26E-04	1.42E-03	2.23E-03	1.40E-02
	Carton board	0.43	0.54	0.16	1.79E-04	6.70E-04	2.26E-03	1.09E-02
Plastic	PS	0.67	1.84	0.99	1.20E-04	1.16E-03	5.01E-03	7.06E-03
	PET	0.93	1.43	0.50	5.95E-04	2.07E-03	5.19E-03	8.24E-02
	HDPE	0.73	0.81	0.54	1.96E-04	8.01E-04	2.93E-03	1.79E-02
	LDPE	0.61	1.26	0.79	2.58E-04	1.14E-03	4.79E-03	1.54E-02
	PP	0.75	0.80	0.50	2.17E-04	8.10E-04	2.80E-03	1.91E-02
Glass	Clear	0.61	0.92	0.31	1.83E-04	1.30E-03	6.94E-03	6.93E-03
	Green	0.84	0.86	0.31	1.70E-04	1.26E-03	6.69E-03	6.66E-03
	Brown	0.55	0.94	0.32	1.87E-04	1.31E-03	7.02E-03	7.03E-03
Metal	Aluminium	0.75	2.74	0.65	1.50E-03	2.62E-03	1.39E-02	6.11E-02
	Steel (Tinplate)	0.50	3.51	0.32	1.40E-03	3.72E-03	1.80E-02	2.34E-01

Appendix Table B-3: Transfer coefficients for the production of paper types with recycling from each grade of recovered paper (the remainder is assumed to go to incineration, last column).

Paper Grade	Newsprint	Other (non-packaging)	Graphic paper	Paper (packaging)	Cardboard	Carton board	*To incineration*
Grade A	0.040	0.012	0.011	0.171	0.450	0.190	*0.126*
Grade B	0.003	0.031	0.000	0.076	0.775	0.022	*0.093*
Grade C	0.491	0.004	0.183	0.008	0.031	0.029	*0.254*
Grade D	0.001	0.018	0.102	0.086	0.149	0.155	*0.489*

Appendix Table B-4: Average capture rates of the two commingling methods observed in the case studies observed in the collectors database (COLLECTORS, 2019) (the number of case studies in the sample that employ each method appear in brackets).

Collection method	Paper	Plastic	Glass	Metal	Composite material
PMD (86*)	61.9%	38.3%	67.9%	47.6%	31.4%
PMD + fibres (27)	47.4%	16.0%	53.8%	22.1%	12.4%
*of which 10 systems comingle plastic and composite material without metal and 9 systems comingle plastic and metal without composite material.					

C. Additional data for WEEE

Appendix Table C-1: Material compositions of the WEEE categories: Small WEEE, IT and Lamps.

Material	Material type	Small WEEE	IT	Lamps
Plastic	ABS	13.18%	8.10%	-
	PA	0.18%	-	-
	PBT	4.07%	-	-
	PC	1.54%	2.10%	-
	PP	5.38%	-	-
	HIPS	5.89%	1.80%	-
	PE	0.37%	-	-
	PVC	0.13%	-	-
	Bromated plastic	0.75%	18.00%	3.70%
	Other	10.33%	-	-
Metal	Aluminium	9.30%	5.00%	14.00%
	Iron	29.00%	36.00%	-
	Copper	17.00%	4.00%	0.22%
	Cadmium	0.01%	0.02%	-
	Mercury	<0.0001%	<0.0001%	0.02%
	Indium	-	<0.0001%	<0.0001%
	Lead	0.57%	0.29%	-
Precious metals	Ag	<0.0001%	<0.0001%	-
	Au	<0.0001%	<0.0001%	-
	Pd	<0.0001%	<0.0001%	-
Crystal		-	19.00%	-
Glass		0.16%	0.30%	77.00%
Other (non-hazardous)		2.14%	5.39%	5.06%

Appendix Table C-2: Environmental impacts of primary production of each material per kg in Electrical and electronic equipment (no substitution of virgin material).

Material	Material type	Substitution rate	GWP (kg CO2-eq.)	FDP (kg oil-eq.)	FEP (kg P-eq.)	MEP (kg N-eq.)	TAP (kg SO2-eq.)	METP (1,4-DCB-eq.)
Plastic	ABS	0.00	4.42E+00	2.24E+00	3.07E-04	2.76E-03	1.24E-02	1.36E-02
	PA	0.00	8.90E+00	3.02E+00	8.22E-04	1.21E-02	3.00E-02	2.49E-02
	PBT	0.00	3.12E+00	1.74E+00	8.42E-04	2.43E-03	1.14E-02	2.55E-02
	PC	0.00	7.78E+00	2.38E+00	2.12E-04	4.73E-03	2.25E-02	7.94E-03
	PP	0.00	2.05E+00	1.71E+00	7.51E-05	1.51E-03	6.12E-03	2.39E-03
	HIPS	0.00	3.50E+00	2.01E+00	4.51E-05	2.23E-03	1.10E-02	1.00E-02
	PE	0.00	2.01E+00	1.73E+00	3.82E-05	1.47E-03	6.39E-03	2.25E-03
	PVC	0.00	2.51E+00	1.30E+00	1.11E-04	1.95E-03	6.45E-03	6.73E-03
	Bromated plastic	0.00	1.34E+01	4.24E+00	3.25E-03	2.25E-02	7.58E-02	1.39E-01
	Other	0.00	4.29E+00	2.02E+00	3.07E-04	3.65E-03	1.33E-02	1.17E-02
Metal	Aluminium	0.00	8.14E+00	1.86E+00	4.64E-03	6.91E-03	4.23E-02	2.02E-01
	Iron	0.00	1.74E+00	4.45E-01	6.30E-04	1.48E-03	6.77E-03	1.07E-02
	Copper	0.00	1.82E+00	5.23E-01	2.29E-02	2.14E-01	5.71E-02	8.69E-01
	Cadmium	0.00	4.11E+00	1.10E+00	2.27E-03	3.80E-03	1.79E-02	5.72E-02
	Mercury	0.00	1.63E+01	3.28E+00	4.49E-03	1.38E-02	1.00E-01	9.55E+01
	Indium	0.00	2.15E+02	5.29E+01	2.48E-01	3.60E-01	1.94E+00	1.04E+01
	Lead	0.00	2.12E+00	4.51E-01	4.40E-03	5.17E-03	4.69E-02	1.41E-01
Precious metal	Ag	0.00	3.44E+02	9.50E+01	1.64E+00	1.24E+00	3.26E+00	1.02E+02
	Au	0.00	1.61E+04	4.83E+03	5.05E+02	8.72E+01	1.62E+02	1.55E+04
	Pd	0.00	5.05E+03	1.45E+03	1.10E+01	8.01E+00	1.50E+03	5.42E+02
Crystal		0.00	4.56E+00	1.21E+00	4.55E-03	4.91E-03	3.18E-02	1.61E-01
Glass		0.00	3.88E+00	1.44E+00	1.12E-03	3.13E-02	1.70E-02	3.13E-02

Appendix Table C-3: Environmental impacts of production of each material per kg, where recycled material is incorporated at the substitution rate, in electrical and electronic equipment.

Material	Material type	Substitution rate	GWP (kg CO2-eq.)	FDP (kg oil-eq.)	FEP (kg P-eq.)	MEP (kg N-eq.)	TAP (kg SO2-eq.)	METP (1,4-DCB-eq.)
Metal	Aluminium	0.75	2.74E+00	6.46E-01	1.50E-03	2.62E-03	1.39E-02	6.11E-02
	Iron	0.50	9.35E-01	2.44E-01	3.44E-04	8.96E-04	3.82E-03	6.47E-03
	Copper	0.50	1.44E+00	4.33E-01	1.17E-02	2.10E-01	4.86E-02	5.29E-01
Precious metal	Ag	1.00	1.71E+01	2.65E+00	1.90E-03	8.58E-03	3.72E-02	1.45E+00
	Au	1.00	1.02E+03	1.58E+02	1.13E-01	5.11E-01	2.22E+00	8.62E+01
	Pd	1.00	5.41E+02	8.38E+01	6.01E-02	2.72E-01	1.18E+00	4.59E+01

D. Additional data for CDW

C-1: Environmental impacts associated with the primary production of each CDW material (per kg).

Material	GWP (kg CO2-eq.)	FDP (kg oil-eq.)	FEP (kg P-eq.)	MEP (kg N-eq.)	TAP (kg SO2-eq.)	METP (1,4-DCB-eq.)
Bricks	2.4E-01	5.9E-02	3.7E-05	1.9E-04	5.8E-04	1.2E-03
Mineral wool	3.4E+00	1.1E+00	1.5E-03	4.0E-02	1.9E-02	4.0E-02
Gypsum (plasterboard)	4.0E-01	1.0E-01	1.3E-04	4.2E-04	2.1E-03	2.9E-03
Sanitary Ceramics	1.9E+00	7.9E-01	5.4E-04	3.6E-04	5.4E-03	2.1E-02

C-2: Environmental impacts associated with recycling each CDW material (per kg).

Material	GWP (kg CO2-eq.)	FDP (kg oil-eq.)	FEP (kg P-eq.)	MEP (kg N-eq.)	TAP (kg SO2-eq.)	METP (1,4-DCB-eq.)
Bricks	4.6E-03	1.6E-03	3.9E-07	1.7E-05	3.2E-05	1.4E-05
Mineral wool	6.5E-01	1.8E-01	1.8E-04	3.3E-04	1.8E-03	5.4E-03
Gypsum (plasterboard)	3.2E-01	4.3E+02	1.7E+02	2.8E-02	5.3E-01	1.4E+00
Sanitary Ceramics	5.1E-04	1.9E-04	2.3E-08	2.3E-06	4.1E-06	9.6E-07

E. Background LCA data used

Appendix Table E-1: List of ecoinvent processes used in (or adapted for) the LCA model.

Activity name	Reference product	Location	Additional information
acrylonitrile-butadiene-styrene copolymer production	acrylonitrile-butadiene-styrene copolymer [kg]	RER	
aluminium production, primary, ingot	aluminium, primary, ingot [kg]	IAI Area, EU27 & EFTA	This process was used for primary production, 75% of the virgin material inputs were replaced by scrap aluminium in closed-loop recycling.
cadmium chloride production, semiconductor-grade	cadmium chloride, semiconductor-grade [kg]	GLO	
clay brick production	clay brick [kg]	RER	
concrete block production	concrete block [kg]	GLO	
containerboard production, linerboard, kraftliner	containerboard, linerboard [kg]	RER	
containerboard production, linerboard, testliner	containerboard, linerboard [kg]	RER	Waste paper content was increased to 0.84kg, virgin fibre input (and associated inputs) reduced by 90%.
copper production, primary	copper [kg]	RER	

corrugated board box production	corrugated board box [kg]	RER	
decabromodiphenyl ether production	decabromodiphenyl ether [kg]	RER	
diesel, burned in building machine	diesel, burned in building machine [MJ]	GLO	
frit production, for ceramic tile	frit, for ceramic tile [kg]	GLO	
funnel glass production, for cathode ray tube display	funnel glass, for cathode ray tube display [kg]	GLO	
glass fibre reinforced plastic production, polyamide, injection moulded	glass fibre reinforced plastic, polyamide, injection moulded [kg]	RER	
glass fibre reinforced plastic production, polyamide, injection moulded	glass fibre reinforced plastic, polyamide, injection moulded [kg]	RER	
glass production, for liquid crystal display	glass, for liquid crystal display [kg]	GLO	
graphic paper production, 100% recycled	graphic paper, 100% recycled [kg]	RER	Primary production: waste paper content replaced by (virgin) pulpwood, closed-loop recycling: 71% of waste paper content replaced by (virgin) pulpwood.
gravel production, crushed	gravel, crushed [kg]	GLO	
gypsum plasterboard production	gypsum plasterboard [kg]	GLO	
indium production	indium [kg]	RER	
kraft paper production, bleached	kraft paper, bleached [kg]	RER	
market for bauxite	bauxite [kg]	GLO	
market for carton board box production, with offset printing	carton board box production, with offset printing [kg]	GLO	Primary production: 1kg (virgin) pulpwood, closed-loop recycling, closed-loop recycling: 0.57 kg (virgin) pulpwood input, 0.43 kg waste paper.
market for copper scrap, sorted, pressed	copper scrap, sorted, pressed [kg]	GLO	
market for gold	gold [kg]	GLO	
market for heat, district or industrial, natural gas	heat, district or industrial, natural gas [MJ]	Europe without Switzerland	

market for indium rich leaching residues, from zinc production	indium rich leaching residues, from zinc production [kg]	GLO	
market for lead	lead [kg]	GLO	
market for palladium	palladium [kg]	GLO	
market for paper, woodfree, uncoated	paper, woodfree, uncoated [kg]	RER	
market for scrap aluminium	scrap aluminium [kg]	Europe without Switzerland	
market for scrap steel	scrap steel [kg]	Europe without Switzerland	
market for silver	silver [kg]	GLO	
market for transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6 [metric ton*km]	RER	
market for waste glass	waste glass [kg]	GLO	
market for waste paper, sorted	waste paper, sorted [kg]	GLO	
market for waste paper, unsorted	waste paper, unsorted [kg]	Europe without Switzerland	
market for waste polyethylene terephthalate, for recycling, sorted	waste polyethylene terephthalate, for recycling, sorted [kg]	Europe without Switzerland	
market for waste polyethylene terephthalate, for recycling, unsorted	waste polyethylene terephthalate, for recycling, unsorted [kg]	Europe without Switzerland	
market for waste polyethylene, for recycling, sorted	waste polyethylene, for recycling, sorted [kg]	Europe without Switzerland	
market for waste polyethylene, for recycling, unsorted	waste polyethylene, for recycling, unsorted [kg]	Europe without Switzerland	
market for waste polypropylene	waste polypropylene [kg]	GLO	Sorting inputs were based on “market for waste polyethylene, for recycling, sorted”.
market for waste polystyrene	waste polystyrene [kg]	GLO	Sorting inputs were based on “market for waste polyethylene, for recycling, sorted”.
market group for electricity, high voltage	electricity, high voltage [kWh]	BE, DE, DK, FI, FR, GB, IT, NL	

mechanical treatment facility construction, waste electric and electronic equipment	mechanical treatment facility, waste electric and electronic equipment [unit]	GLO	
mercury production	mercury [kg]	GLO	
Packaging glass production, brown	packaging glass, brown [kg]	RER w/o CH+DE	
packaging glass production, brown, without cullet	packaging glass, brown [kg]	GLO	
packaging glass production, green	packaging glass, green [kg]	RER w/o CH+DE	
packaging glass production, green, without cullet	packaging glass, green [kg]	GLO	
packaging glass production, white	packaging glass, white [kg]	RER w/o CH+DE	
packaging glass production, white, without cullet	packaging glass, white [kg]	GLO	
paper production, newsprint, recycled	waste newspaper [kg]	Europe without Switzerland	Waste paper content was increased to 0.83kg, deinking compounds were increased by 12%, virgin fibre input (and associated inputs) were reduced by 12%.
paper production, newsprint, virgin	paper, newsprint [kg]	RER	
paper production, woodfree, uncoated, 30% recycled content, at integrated mill	paper, woodfree, uncoated [kg]	CA-QC	Waste paper content was decreased by 1%, virgin fibre input was increased by 1%.
pig iron production	pig iron [kg]	GLO	
polycarbonate production	polycarbonate [kg]	RER	
polyethylene production, high density, granulate	polyethylene, high density, granulate [kg]	RER	
polyethylene production, high density, granulate, recycled	polyethylene, high density, granulate, recycled [kg]	Europe without Switzerland	Process inputs were adapted to reflect virgin material substitution rates (Table A-2).
polyethylene production, low density, granulate	polyethylene, low density, granulate [kg]	RER	This process was adapted for the closed-loop recycling of LDPE by replacing 61% of the virgin material inputs from “waste polyethylene, for recycling, sorted”.
polyethylene terephthalate production, granulate, amorphous	polyethylene terephthalate, granulate, amorphous [kg]	RER	

polyethylene terephthalate production, granulate, amorphous, recycled	polyethylene terephthalate, granulate, amorphous, recycled [kg]	Europe without Switzerland	Process inputs were adapted to reflect virgin material substitution rates (Table A-2).
polypropylene production, granulate	polypropylene, granulate [kg]	RER	As there was no process for recycled polypropylene, this process was adapted for closed-loop recycling based on “waste polyethylene, for recycling, sorted”, replacing the virgin material inputs by 75%.
polystyrene foam slab production	polystyrene foam slab [kg]	RER	
polystyrene foam slab production, 100% recycled	polystyrene foam slab [kg]	RoW	Process inputs were adapted to reflect virgin material substitution rates (Table A-2). Virgin material inputs were sourced from “polystyrene foam slab production”.
polystyrene production, high impact	polystyrene, high impact [kg]	RER	
polyvinylidenchloride production, granulate	polyvinylidenchloride, granulate [kg]	RER	
primary lead production from concentrate	lead [kg]	GLO	
propane, burned in building machine	propane, burned in building machine [MJ]	GLO	
sputtering, indium tin oxide, for liquid crystal display	sputtering, indium tin oxide, for liquid crystal display [m3]	RER	
stone wool production	stone wool [kg]	GLO	
tin plated chromium steel sheet production, 2 mm	tin plated chromium steel sheet, 2 mm [m^2]	RER	This process was used for primary production, 50% of the virgin material inputs were replaced by scrap steel in closed-loop recycling.
treatment of electronics scrap, metals recovery in copper smelter	electronics scrap [kg]	GLO	
treatment of precious metal from electronics scrap, in anode slime, precious metal extraction	precious metal from electronics scrap, in anode slime [kg]	GLO	
treatment of scrap aluminium, municipal incineration	scrap aluminium [kg]	Europe without Switzerland	
treatment of scrap copper, municipal incineration	scrap copper [kg]	Europe without Switzerland	

treatment of scrap steel, inert material landfill	scrap steel [kg]	Europe without Switzerland	
treatment of scrap steel, municipal incineration	scrap steel [kg]	Europe without Switzerland	
treatment of used fluorescent lamp	used fluorescent lamp [kg]	GLO	
treatment of used liquid crystal display, mechanical treatment	used liquid crystal display [kg]	GLO	
treatment of waste aluminium, sanitary landfill	waste aluminium [kg]	RoW	
treatment of waste brick, collection for final disposal	waste brick [kg]	GLO	
treatment of waste electric and electronic equipment, shredding	waste electric and electronic equipment [kg]	GLO	
treatment of waste glass from unsorted public collection, sorting	glass cullet, sorted [kg]	RER	
treatment of waste glass, municipal incineration	waste glass [kg]	RoW	
treatment of waste glass, sanitary landfill	waste glass [kg]	GLO	
treatment of waste gypsum plasterboard, recycling	waste gypsum plasterboard [kg]	GLO	
treatment of waste gypsum, sanitary landfill	waste gypsum [kg]	Europe without Switzerland	
treatment of waste mineral wool, collection for final disposal	waste mineral wool [kg]	Europe without Switzerland	
treatment of waste mineral wool, inert material landfill	waste mineral wool, for final disposal [kg]	Europe without Switzerland	
treatment of waste mineral wool, recycling	waste mineral wool [kg]	Europe without Switzerland	
treatment of waste paperboard, inert material landfill	waste paperboard [kg]	RoW	
treatment of waste paperboard, municipal incineration	waste paperboard [kg]	RoW	1.99 MJ/kg electricity and 3.89 MJ/kg of heat were assumed to be recovered.
treatment of waste plastic, consumer electronics, municipal incineration	waste plastic, consumer electronics [kg]	GLO	

treatment of waste polyethylene terephthalate, municipal incineration	waste polyethylene terephthalate [kg]	RoW	5.04 MJ/kg electricity and 9.71 MJ/kg of heat were assumed to be recovered.
treatment of waste polyethylene terephthalate, sanitary landfill	waste polyethylene terephthalate [kg]	RoW	
treatment of waste polyethylene, municipal incineration	waste polyethylene [kg]	RoW	2.97 MJ/kg electricity and 5.81 MJ/kg of heat were assumed to be recovered.
treatment of waste polyethylene, sanitary landfill	waste polyethylene [kg]	RoW	
treatment of waste polypropylene, municipal incineration	waste polypropylene [kg]	RoW	5.55 MJ/kg electricity and 10.69 MJ/kg of heat were assumed to be recovered.
treatment of waste polypropylene, sanitary landfill	waste polypropylene [kg]	RoW	
treatment of waste polystyrene, municipal incineration	waste polystyrene [kg]	RoW	4.20 MJ/kg electricity and 8.15 MJ/kg of heat were assumed to be recovered.
treatment of waste polystyrene, sanitary landfill	waste polystyrene [kg]	RoW	
unreinforced concrete production, with cement CEM II/A	concrete, normal [m3]	GLO	

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