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The Potential of Reducing Carbon Footprint Through Improved Sorting

Fredrika Olsson

UPPSALA
UNIVERSITET

Teknisk- naturvetenskaplig fakultet
UTH-enheten

Besöksadress:
Ångströmlaboratoriet
Lägerhyddsvägen 1
Hus 4, Plan 0

Postadress:
Box 536
751 21 Uppsala

Telefon:
018 – 471 30 03

Telefax:
018 – 471 30 00

Hemsida:
http://www.teknat.uu.se/student

Abstract

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Almost five million tonnes of household waste was generated in Sweden in 2018, half of which was residual waste sent for incineration with energy recovery. For materials that can not be recycled or biologically treated, incineration with energy recovery is considered a preferred management option. The issue is that the fraction for residual waste contains considerable amounts of wrongly sorted materials, such as food waste and plastic packaging, which can be recycled or biologically treated, thus causing a smaller environmental impact.

To quantify the composition and waste quantities of the wrongly sorted materials a waste composition analysis of the residual waste from four community bins in Västmanland county was conducted. The analysis revealed that about two-thirds of the waste was wrongly sorted and only one-third was actual residual waste. Life cycle analysis was subsequently used to calculate the carbon footprint of the wrongly sorted food waste and plastic packaging waste as well as the carbon footprint from optimal sorting and treatment of the materials. The investigation concluded that for food waste, anaerobic digestion caused a smaller climate impact than incineration with energy recovery and for plastic packaging, recycling generated a smaller climate impact than incineration with energy recovery. The size of the carbon footprint for the different management methods was in line with the priority order given in the waste hierarchy, stated in Swedish legislation. However, the size of the potential climate savings partly depended on the choices made in the life cycle analysis where the most sensitive parameters were related to external production of heat, polymer resin and vehicle fuel. If the potential climate savings is extrapolated for VafabMiljö's entire collecting area, the total climate savings per year would be 8 263 tonnes of carbon dioxide equivalents per year for food waste and 2 070 tonnes of carbon dioxide equivalents per year for plastic packaging waste. This would be equivalent to driving 1 250 laps around the Earth with a car every year or flying 14 900 times Sweden–Thailand back and forth every year.

Keywords: Waste composition analysis, Life cycle analysis, Carbon footprint, Residual waste, Food waste, Plastic packaging

Handledare: Johanna Olsson och Marianne Allmyr
Ämnesgranskare: Bojana Bajzelj
Examinator: Alexandru Tatomir
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Referat

Potentialen att minska klimatavtrycket genom en ökad källsortering

Fredrika Olsson

Nästan fem miljoner ton hushållsavfall genererades i Sverige under 2018, varav ungefär hälften skickades till energiåtervinning. För avfall som inte kan materialåtervinnas eller behandlas biologiskt anses energiåtervinning vara den bästa metoden för avfallshantering. Problemet är att stora mängder återvinningsbart material såsom matavfall och plastförpackningar felaktigt hamnar i restavfallet när det istället hade kunnat återvinnas och på så sätt medfört en mindre miljöpåverkan.

För att kvantifiera samansättning och avfallsmängder av det felaktigt sorterade materialet, gjordes en plockanalys på restavfallet från fyra miljöbodar i Västmanland. Analysen visade att ungefär två tredjedelar av materialet var felaktigt sorterat och endast en tredjedel utgjordes av övrigt restavfall. Livscykelanalys användes därefter för att beräkna klimatavtrycket för det felaktigt sorterade matavfallet och för plastförpackningarna som återfanns i restavfallet såväl som klimatavtrycket för optimal sortering och hantering av materialen. Ordningen i avfallshierarkin visade sig stämma väl överens med klimatavtrycket från de olika behandlingsmetoderna i det undersökta området. För matavfall innebar rötning en lägre klimatpåverkan än energiåtervinning och för plastförpackningar medförde materialåtervinning en lägre klimatpåverkan än energiåtervinning. Storleken på besparingarna av växthusgaser berodde dock till viss del på val av inparametrar och de faktorer som främst påverkade var alternativ produktion av värme, plaståvara och drivmedel. Om resultaten extrapoleras över hela VafabMiljös upphämtningsområde så skulle de totala klimatbesparingarna för matavfall vara 8 263 ton koldioxidekvivalenter per år och för plastförpackningar 2 070 ton koldioxidekvivalenter per år. Dessa besparingar är jämförbara med bilkörning motsvarande 1 250 varv runt jorden varje år eller 14 900 tur- och returresor med flyg Sverige–Thailand varje år.

Nyckelord: Plockanalys, Livscykelanalys, Klimatavtryck, Restavfall, Matavfall, Plastförpackningar

Preface

This master thesis is part of the Master's Programme in Environmental and Water Engineering at Uppsala University and the Swedish University of Agricultural Sciences. The thesis covers 30 Swedish academic credits and was conducted in collaboration with VafabMiljö, Mälarenergi and Hallstahem as part of the project *Plocka, motivera and sortera* where another student, Isabella Viman, also were involved. Supervisors were Johanna Olsson, waste strategist at VafabMiljö and Marianne Allmyr, energy strategist at Mälarenergi and the subject reader was Bojana Bajzelj at the Department of Energy and Technology at the Swedish University of Agricultural Sciences. Examiner were Alexandru Tatomir at the Department of Earth Sciences at Uppsala University.

I would like to thank everyone who contributed to the realisation of this thesis, I am so grateful for the support I have gained. Thank you to Bojana Bajzelj for valuable inputs and discussions, thank you to Johanna Olsson and Marianne Allmyr who has always been available and eager to help. Thank you to Johanna Olsson, Anna Boldt, Anna-Karin Lindfors, Isabella Viman, Marianne Allmyr and Katarina Hogfeldt-Forsberg for helping execute the waste composition analysis. Furthermore, I would like to express my deepest gratitude to my family and friends that have supported me on a personal level throughout this thesis as well as along my education.

Fredrika Olsson
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Populärvetenskaplig sammanfattning

Vikten av att sortera rätt

Fredrika Olsson

Genom små förändringar går det att göra stor skillnad. Om alla i Sverige skulle slänga plast och matavfall i rätt kärl, skulle det spara klimatutsläpp lika stora som att 5 % av befolkningen årligen skulle flyga till Thailand eller utsläpp motsvarande att köra 40 000 varv runt jorden i en bil varje år. Tänk hur stora utsläpp det går att undvika när många personer gör en liten förändring!

Varje år genereras nästan fem miljoner ton hushållsavfall i Sverige. Ungefär hälften av avfallet sorteras som brännbart avfall och eldas upp. I denna studie undersöktes det brännbara avfallet från fyra miljöbodar i Västmanland och så mycket som två tredjedelar av innehållet visade sig vara felsorterat. Mat, plast- och pappersförpackningar var vanligt förekommande och hade kunnat återvinnas om de sorterats rätt. Att elda upp material som kan återvinnas visade sig leda till onödiga utsläpp och resursslöseri, då avfallet istället hade kunnat omvandlas till nya produkter. Förbränning av material som inte går att återvinna är dock positivt eftersom användbar fjärrvärme och el då produceras.

Utöver det primära syftet att behandla avfallet produceras även andra mervärden vid de olika metoderna för avfallshantering. Vid rötning bildas till exempel biogas som kan användas som drivmedel för bilar och vid materialåtervinning bildas material som kan användas till nya förpackningar. De olika metoderna för att behandla avfallet genererar olika utsläpp av växthusgaser. Samtliga utsläpp som bildas från förbränning, materialåtervinning respektive rötning undersöktes för att beräkna mängden växthusgaser som kan undvikas vid rätt sortering. För att möjliggöra en rättvis jämförelse justerades även utsläppen utifrån de fördelar som de olika metoderna genererar.

Den stora utmaningen med att ställa om samhället för att begränsa den globala uppvärmningen kan skapa hopplöshet. Men det går att göra skillnad även genom små medel, något resultaten från denna studie har visat. Genom att kommunicera betydelsen av små beteendeförändringar är motivationen att kunna minska utsläppen av växthusgaser från avfall och på samma gång inge hopp om att det går att göra skillnad.

Contents

1 Introduction

The global consumption is continuously rising due to increasing populations and an increased per capita consumption, generating growing waste quantities (Svenska FN-förbundet 2017). Despite increasing levels of waste, the waste management is globally poor thus posing a risk for natural resource depletion in addition to adverse climate impact. By improving the waste management, resources in products can be recirculated, thus avoiding negative environmental impacts such as emissions of greenhouse gases. Improving the waste management also gives rise to economical and social benefits as it for example can provide employments and improve human health (UNDP 2020).

United Nations has created a set of sustainable development goals, where one specifically addresses the issues of unsustainable consumption and production. Their proposed strategies to deal with these issues include reducing waste quantities along with raising the general public's awareness on sustainability (ibid.). Waste quantities can be reduced by several means. In the Swedish Environmental Code, the hierarchy of different management options is described to minimise environmental impact. Waste prevention is stated as the most preferable measure (SFS 1998:808), which can be implemented by influencing consumer behaviours. However, complete elimination of waste is not always possible and in those instances it is favorable that the waste management generate some useful output product. If feasible, the material shall be directly reused, secondly recycled so that new materials are generated and least preferably incinerated to produce useful energy (ibid.).

The waste management system in Sweden is technically well developed and the infrastructure to manage the waste in accordance to the waste hierarchy is available. Swedish recycling levels are similar to other European countries but use incineration with energy recovery (further referred to as simply incineration in this report) to a greater extent, thus producing useful energy instead of depositing the waste on landfills (Sveriges avfallsportal sopor.nu 2020). Despite the well developed system, individual responsibilities and knowledge about sorting have a great impact on the treatment of different materials in the household waste. Recyclable materials are commonly sorted incorrectly and put in the residual bin, so that the material is subsequently incinerated (Leander, Zeidlitz & Åberg 2016). This causes unnecessary environmental impact since the materials in accordance with the waste hierachy can be treated in a more resource efficient manner (SFS 1998:808).

In 2018 an average person in Sweden generated 466 kg of household waste. Of this waste 50 % was incinerated, 31 % was material recycled and 16 % was biologically treated (biowaste treated by anaerobic or aerobic digestion) (Avfall Sverige 2019a) (Avfall Sverige 2019b). Of the 50 % that went to incineration, a significant part could have been treated in a more resource efficient way according to the waste hierarchy. With the aid of waste composition analysis (WCA), the composition of the waste in different fractions can be manually analysed. Avfall Sverige conducted a review of WCA of the residual waste from apartments with separate collection of food waste executed in 2013-2016 and it indicated that 66 % of the material could have been recycled or biologically treated(Leander, Zeidlitz & Åberg 2016).

1.1 Aim and Research Questions

The aim of the collaborative project *Plocka, motivera and sortera* was to investigate how individual behaviours associated with waste sorting can be affected. By acquiring information regarding individual incentives as well as barriers to better sorting of waste, the ambition is to influence individuals so that less material is put in the fraction for residual waste and more material is put in the fractions for recycling and biological treatment. For the involved companies this is important information to enable them to reach their separate environmental goals.

The aim of this part of the project was to investigate the composition of the residual waste in the investigated area and to analyse the climate impact associated with different waste management options. This information is intended to be used to inform residents about the climate impact of their behaviour and thus try to influence their behaviour.

In order to reach the aim of this report the following questions are investigated:

- What is the composition of the residual waste in the investigated area?
- What is the carbon footprint of different waste management options for food waste and plastic packaging waste in the investigated area?
- To what extent can the carbon footprint be reduced by improved sorting?

1.2 Limitations of the Study

The conducted WCA does not cover bulky waste, industrial waste, waste from other housing types than multi-family residential, waste from properties that lack separate collection of food waste, or waste from other collection systems than above ground containers. The conducted life cycle analysis does not investigate possible climate savings from any other materials in the residual waste than food waste and plastic packaging.

Certain adjustments had to be made to the study design due to the pandemic COVID-19, which started half-way through the project. The original idea was to execute two WCA, one in the beginning of the project and another one in the end of the project. The objective of the first WCA was to identify a reference level for the residual waste at the start of the project. With this information in addition to results from the conducted interviews (of which Isabella Viman was responsible), measures to influence the behavior of the residents were going to be proposed and implemented. The effect of the implemented measures were then planned to be evaluated with a second WCA. Because of COVID-19, the proposed measures could not be implemented and neither could a second WCA be conducted. This study therefore became a theoretical analysis of possible measures to improve the sorting and the benefits this could lead to regarding climate impact. To fulfill the aim of the project, further studies are needed to evaluate the effect of the proposed measures.

2 Theory

2.1 Legislation and Goals

Waste is defined in the Swedish Environmental Code chapter 15, as an object or material that the owner discards, intend to discard or is obligated to discard. There are several means in which waste quantities can be reduced and the priority order is described in the waste hierarchy which is also stated in the Environmental Code chapter 15 (SFS 1998:808).

The shape of the waste hierarchy, depicts the waste quantities and can be seen in figure 1. At the top of the hierarchy the waste quantities are the largest and for every step down the quantities decrease to ideally become minimal at the bottom. If possible, waste prevention is the preferred choice as it saves the resources and greenhouse gases being consumed and generated in the production of the waste material in the first place. If it is not possible to prevent the waste, then the material ought to be reused, recycled, energy recovered and least preferably disposed (SFS 1998:808).

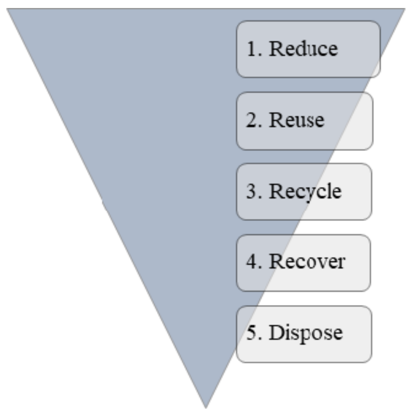

Figure 1: *The waste hierarchy*

As stated by the Environmental Code, every municipality is obligated to collect and treat the household waste generated (excluding materials where the producer's responsibility apply) (SFS 1998:808). VafabMiljö has received the responsibility for collection and treatment of household waste by the municipalities in Västmanland County and the municipality of Heby and Enköping (VafabMiljö 2018). For materials within certain fields, the producer's responsibility apply. It means that the producer is responsible for the collection and treatment of waste generated from its products (SFS 1998:808). The producer's responsibility for now (june 2020) applies to packaging materials, electric and electronic equipment, batteries and medicines (Naturvårdsverket 2019a). The producer's responsibility also applied to newspapers until April 2020 (Miljödepartementet 2020). Beyond the liabilities of municipalities and producers, it is also a legal obligation for every resident to sort out packaging materials, newspapers and electronic waste, which is further described in the Waste Ordinance (SFS 2011:927).

In addition to collection and treatment, the municipalities also have to set up a waste plan, containing information on their strategies to reduce waste quantities and their work to comply with the waste hierarchy (SFS 1998:808). Again, VafabMiljö is responsible for doing this for the municipalities of Västmanland County and the municipality of Heby and Enköping (VafabMiljö 2018). In the proposal of the regional waste plan 2020-2030, VafabMiljö presents the following goals (ibid.):

- By 2030, waste quantities have decreased with 7 % compared to 2020
- By the latest 2030, a minimum of 60 % of the collected household waste will be sorted out in the recyclable fractions
- By the latest 2030, a maximum of 35 % of the collected household waste will be treated by incineration

The housing corporation Hallstahem is also interested in improving the waste sorting from their residents as they have set up an environmental goal to reduce emissions of greenhouse gases from the waste in their communal bins (Hallstahem n.d.). Because of a growing demand of energy with low climate impact, the energy producer Mälarenergi wants to reduce the quantities of plastic packaging with fossil origin present in the residual waste.[1]

2.2 The Waste Management System in Västmanland County

VafabMiljö has set up a sorting guide for individuals, describing how to sort different materials (VafabMiljö 2019). For the sorting and collection of household waste in areas with multi-family residential, there are community spaces where different materials can be sorted in separate containers. These spaces will henceforward be called community bins. In the community bins collection of residual waste, food waste, paper packages, plastic packages, metal packages, glass packages, newspapers, batteries and light sources (light bulbs and luminous lamps) are provided. After collection, the different waste fractions are managed separately which is further described below (see section 2.2.1-2.2.3).

2.2.1 Management of Food Waste

Food waste is collected and transported to the biogas (anaerobic digestion) facility at Gryta waste treatment plant in Västerås. Anaerobic digestion is classified under the third step in the waste hierarchy: recycling. Prior to the anaerobic digestion, the material has to go through pretreatment and hygienisation.

[1] Marianne Allmyr, energy engineer, Mälarenergi, personal communication 9/6/2020

In the pretreatment, contaminants such as packages are removed by grinding and sieving the material. The remaining material is mixed with water, creating a slurry. To prevent the growth of unwanted bacteria, hygienisation of the slurry is done at 70 °C.[2]

The anaerobic digestion processes is subsequently carried out in three steps: hydrolysis, fermentation and ultimately anaerobic oxidation. The digestion is operated mesophilic (37–42 °C) (Schnürer et al. 2019) and the retention time in the anaerobic digester is 20 days.[3]During this time the microbes anaerobically digest the molecules in the food waste and thus create raw biogas: a mix of mostly methane (65 %) and carbon dioxide (35 %). Before the biogas can be used as fuel, it needs to be cleaned from contaminants and upgraded to contain at least 97 % of methane (VafabMiljö n.d.). The upgraded biogas from VafabMiljö's biogas facility contain on average 98-99 % of methane.[3] In 2019, the facility on average consumed and produced the following resources (see table 1).

Table 1: *Consumed and produced resources from anaerobic digestion of one tonne of food waste at Gryta waste treatment plant in Västerås in 2019* [3]

	Consumed resources
Heat	149 kWh
Electricity (anaerobic digestion)	67.3 kWh
Electricity (upgrading of gas)	90.4 kWh
	Produced resources
Raw biogas	138 Nm^{3*}
Upgraded biogas	104 Nm^{3*}
Biofertiliser (liquid)	1.18 tonnes
Biofertiliser (solid)	0.13 tonnes

* 1 Nm^3 = 1 m^3 at 0 °C and 1 atmosphere of pressure

The digestate from the biogas plant is used for fertilising and is certified as a complete fertiliser (ibid.). Analyses of the digestate during three months in 2019 revealed the average nutrient content in the solid and liquid fertiliser (see table 2).

[2] Olga Korneevets, process engineer, VafabMiljö, personal communication 29/04/2020
[3] Olga Korneevets, process engineer, VafabMiljö, personal communication 9/03/2020

Table 2: *Average nutrient content in one tonne of the digestate from Vafab-Miljös biogas facility during three months in 2019 (VafabMiljö 2020a) (Vafab-Miljö 2020b)*

	Solid biofertiliser	Liquid biofertiliser
N-tot	9.07 kg	2.94 kg
NH4-N	2.73 kg	2.15 kg
P-tot	1.70 kg	0.210 kg
K-tot	1.31 kg	1.05 kg

The information given regarding the biogas facility is for the operation in 2019. However, the facility and the processes involved will change since a new facility is to be built (according to the plan it will be in full operation by the Summer of 2021). The new facility will hold two digesters instead of one, so that the food waste can be anaerobically digested twice. This will increase the biogas production. The suspension buffer tank will be larger so that greater waste quantities can be collected and stored, which will increase the production of biogas. The hygienisation of the waste will be executed at a lower temperature which will decrease the heat consumption. In addition, the upgraded biogas will be liquefied so that higher amounts can be stored and the use of natural gas will decrease when the produced amount of biogas is too low.[4]

2.2.2 Management of Packaging Waste

Packaging waste is divided into different fractions depending on the material. Common for all packaging materials is that they are collected and transported to Gryta waste treatment plant in Västerås where baling occur. From there the separate materials are transported to different locations for sorting and recycling. Recycling is classified under the third step in the waste hierarchy. Since plastic packaging was the only investigated packaging fraction in this study, it is the only one that is further described.

Plastic packaging is transported to Motala sorting facility where the bales are shredded to separate the material within them. The material subsequently goes through a number of sorting steps, where multiple machines sort the material by size and density and wrongly sorted metal are removed by magnets (Svensk plaståtervinning n.d.).

[4] Olga Korneevets, process engineer, VafabMiljö, personal communication 4/03/2020

Ultimately the material is sorted by color and polymer type by the means of infrared light and sorted fractions of polypropylene (PP), high-density polyethylene (HDPE), low-density polyethylene (LDPE) and Polyethylene terephthalate (PET) are sent for recycling (Svensk plaståtervinning n.d.).

Of the material that arrived to Motala sorting facility in 2019, conducted WCA at the facility reveal that about 30 % was wrongly sorted waste (for example food waste and other packaging materials).[5] Of the plastic packages that arrived to the facility, Svensk Plaståtervinning announces that about 50 % was sorted into bales for recycling and the remaining 50 % was rejected and sent to incineration.[6]However, there are sources that argue for a lower recycling rate. For example Avfall Sverige, argue that the actual percentage of plastic packages that can be recycled is only about 35 % of the packages put on market (Holmström & Solis 2020). Common reasons why plastic packages are rejected include material design issues that prevent the detection of different polymers but it can also be due to a lack of demand for certain types of recycled polymers. After sorting, the polymer fractions still contain some impurities. In 2019, the baled and sorted polymers from Motala sorting facility had a purity of 95%.[7]

After sorting, the different types of plastic is transported to recycling facilities within Europe, for example in Germany, The Netherlands and Finland. [8]Every polymer type is recycled separately. The most common method for recycling of polymers is the use of mechanical recycling (Plastics Europe n.d.). In this type of recycling the polymers are degraded mechanically into flakes which are washed and subsequently melted into granulates. Due to the mechanical wearing the quality of the polymer molecules is gradually decreasing until it is not possible to recycle anymore (Terselius n.d.). The material in a plastic container can normally be recycled up to seven times (FTI n.d.).

Different plastic types generate different quantities of emissions, both during production, recycling and potential incineration. Therefore it is of importance to know the composition of different polymer types present in the generated waste. With the assumption that the polymer composition in plastic packaging in the waste is representative to the demand of polymers from plastic manufacturers in Europe, the composition of the most common polymers used in plastic packaging is: 34 % of PP, 31 % of LDPE, 22 % of HDPE and 13 % of PET (Nordin et al. 2019). Also polystyrene (PS), polyamide (PA) and Polyvinyl alcohol (EVOH) is polymers used in plastic packaging (ibid.) but these polymers are not sent for recycling in Sweden as of today 2020 and were thus not investig-

[5] Amanda Nilsson, Marketing, Svensk Plaståtervinning, personal communication 14/04/2020

ated.[8] The assumption is a rough estimate and will only give an approximate composition. It is also worth to emphasise that these values for plastic demand does not only cover plastic containers but also other plastics.

2.2.3 Management of Residual Waste

The residual waste is collected and transported to Mälarenergi's incineration plant in Västerås. Incineration is classified under the forth step: energy recovery, in the waste hierarchy. Prior to the incineration, the material has to go through a preparation step where it is mixed and shredded to become more homogeneous. Materials of metal, glass, ceramics and stones are sorted out and rejected. Ultimately, the material is prepared and ready to be incinerated. By incineration of the waste and flue gas purification, district heat and electricity is generated in several steps. The incineration occurs in a boiler where the produced heat is carried by flue gases. The heat converts liquid water into water steam, that runs a turbine and generates electricity. The remaining energy stored in the water steam is distributed as district heating. The flue gases are purified, that way solidifying most environmentally undesired particles and generating further district heating by condensation of the gas. The remaining emissions are released to the atmosphere (Mälarenergi n.d.[a]).

In 2019, Mälarenergi on average emitted 0.504 tonnes of CO_2 equivalents (CO_2e) per tonne incinerated waste.[9]The incineration also consumed and produced resources (see table 3). The energy consumed in the incineration and flue gas purification process on a yearly basis is internally produced.

Table 3: *Average quantities of consumed and produced resources from incineration of one tonne of waste at Mälarenergi's combustion plant in 2019* [9]

	Consumed resources	Produced resources
Heat	8.87 kWh	2660 kWh
Cool	0 kWh	84.8 kWh
Electricity	158 kWh	870 kWh

[8] Amanda Nilsson, Marketing, Svensk Plaståtervinning, personal communication 17/04/2020
[9] Marianne Allmyr, energy engineer, Mälarenergi, personal communication 17/03/2020

2.3 Barriers to Better Sorting of Waste

In another study, interviews were conducted with residents in two of the investigated areas. The interviews revealed that most people think it is important to sort their waste and claim they at least partially sort their waste. Laziness and stress were pointed out as main obstacles for not sorting. However, when analysing the answers it was clear that a lack of knowledge impacts on their sorting as well. For example, many residents believed that packages have to be cleaned and therefore of laziness the package was disposed in the residual bin. More information about the interviews and how they were carried out can be found in Isabella Viman's report. [10]

[10] Isabella Viman. (Unpublished). Swedish University of Agricultural Sciences. Department of Economics/ Environmental Economics and Management Master's Programme

3 Materials and Methods

To answer to question formulations, waste composition analyses and life cycle analyses of climate impact were used. Waste composition analysis (WCA) is a method to manually analyse the composition of the waste. The waste is sorted into a set number of fractions that are weighed separately to obtain information about the content of the investigated waste (Leander 2017). Life cycle assessment (LCA) is a method to analyse the environmental impact of a product over their entire life cycle. This includes all processes affecting the environment, starting from the extraction of raw materials to the manufacturing, transport, usage and ultimately end-of-life (disposal/recycling) (Klöpffer & Grahl 2014).

3.1 Waste Composition Analysis

3.1.1 Scope of Survey

The material for the analyses were collected from four different communal bins from multi-family residential (see the red dots in figure 2) and an explanation of the denotations used in the figure and henceforth in this report can be seen in table 4 below. The communal bins were chosen in collaboration with Lina Andersson from Hallstahem.[11] The idea was to include what Hallstahem considered to be both poorly functioning along with better functioning community bins.

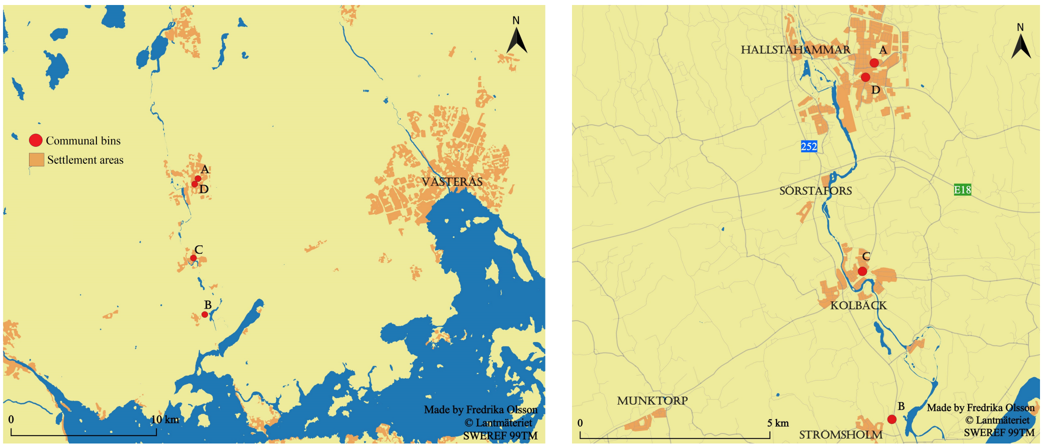

Figure 2: *Maps with investigated community bins marked with red dots*

[11] Lina Andersson, marknads- och kommunikationschef, Hallstahem, personal communication, 14/01/2020

Table 4: Denotations for the investigated addresses in the scope area

Denotation	Address
A	Snevringevägen 49
B	Sofielundsvägen 22–24
C	Södra Kapellgatan 1
D	Surbrunnsvägen 4

Due to limitations in time and resources a larger number of community bins and waste quantities were not considered possible to investigate. Therefore, the analysis shall not be viewed as a statistically accurate study representing a bigger area but more as a sample of the investigated area.

3.1.2 Execution of the Analysis

The WCA was conducted on Bränsleplattan at Gryta waste treatment plant in Västerås (see figure 3 and figure 4). The analysis took two days to complete and involved a total of almost 800 kg of residual waste. Among the group executing the analysis, two persons were experienced in the procedure of doing WCA and were both involved in VafabMiljö's comprehensive WCA in 2010 (Bergh, Boldt & Lindfors 2010).

Figure 3: *The content from one plastic bag which depicts the analysed bags well Photo by: Anna Boldt*

Figure 4: *Waste composition analysis in operation*
Photo by: Anna Boldt

The WCA overall followed the procedure for household waste developed by Avfall Sverige, however in a smaller scale than suggested (Leander 2017). According to the aim of the project, the number of fractions that were used were limited to eight: food waste, paper packages, plastic packages, glass packages, metal packages, newspapers, hazardous waste & electric waste and residual waste. The hazardous and electric waste were merged into one fraction since the quantity of these fractions is so small (normally up to a few percentage of the total weight of the residual waste (Leander, Zeidlitz & Åberg 2016)).

VafabMiljö's sorting guide was used as a guideline for how to do the sorting (VafabMiljö 2019). It was nonetheless not always clear how to sort the material in the waste. In those instances the objects were discussed amongst the group to determine the most suitable fraction. Some objects were so torn apart that it was difficult to know the origin of the object, for example small plastic pieces that may have originated from a container or from other plastic objects. Another topic that was debated was the vague distinction between bulky waste and household waste. Metal candle holders were one of the few exceptions where the waste were not sorted in compliance with the sorting guide. Instead it was sorted as metal containers. Since 2015, the national guidelines define these as bulky waste (Gästrike återvinnare n.d.) and this is also the information that VafabMiljö is giving in their guidelines. However, the information given on the leaflet at the community bins still say that they are supposed to be sorted as a metal container in the household waste.

Part of the plastic containers consisted of plastic bags with the purpose of carrying the residual waste. This plastic was considered inevitable as the waste needs to be contained by something. To estimate the percentage of the inevitable plastic packages, all plastic bags with the function as garbage bags in one container from one of the communal bins were sorted and weighed separately.

To be able to compare the collected data with previous studies the data were converted from kg waste per community bin and week to kg waste per individual and year. The number of households per community bin was given by Lina Andersson from Hallstahem and is between 29–37 for the investigated area.[12] The number of individuals in Hallstahammar for rented apartments is 1.8 individuals per household (SCB 2019). To visualise the composition of the residual waste, weight percentage for the different waste fractions in the waste were calculated.

3.1.3 Materials

In the WCA, one scale was used for all weighings including the weighing of the hazardous waste and electric waste. This scale was of the brand Flintab våg and had an accuracy of ± 0.25 kg. According to Avfall Sverige's guidelines it is preferable to have access to two scales with different sensitivity, one for the bigger fractions with an accuracy of 0.1 kg and a special one for the hazardous waste and electric waste with an accuracy of 1-2 g (Leander 2017). The scale that was used for the bigger fractions had an accuracy of the same magnitude as the guidelines but for the smaller fractions, the uncertainty became a greater part of the result.

In this study, the weight did not change when weighing a bin twice, probably because of the considerably big uncertainty of the scale. Therefore, the bins were only weighted once each. During the weighing of two of the bins, the scale could not find equilibrium but the scale kept shifting between two adjacent values. For these cases a mean value of the two shifting values were recorded.

The uncertainty of the data obtained by the scale was calculated by the formula of combined standard uncertainty (see equation 1)(Mario Zilli 2013).

[12] Lina Andersson, marknads- och kommunikationschef, Hallstahem, personal communication, 14/01/2020

$$u_{tot} = \sqrt{u_1^2 + u_2^2 + ... + u_n^2} \quad (1)$$

u_{tot} is the combined uncertainty of the individual uncertainties u_1, u_2 and so on. The scale's uncertainty for each individual weighing was ±0.25.

3.2 Life Cycle Analysis of Climate Impact

A proper LCA, involves the assessment of multiple impact categories (such as climate impact, euthrophication and acidification) (Klöpffer & Grahl 2014). In this study only the aspect of climate impact was investigated and therefor it is not an extensive LCA but a carbon footprint of a product (CFP). Guidelines on CFP has emerged and can be found in ISO 14067:2018. However, the guidelines for CFP follows a similar methodology as a LCA but for the single impact category: climate change (Ekvall 2019). Therefore LCA methodology stated in ISO 14040 and ISO 14044, has been applied in this study.

A life cycle assessment normally contain four phases: the goal and scope definition, the life cycle inventory analysis, the life cycle assessment and the interpretation. In the goal and scope definition, details about the objective of the study, target groups, system boundaries, functional unit and the type of LCA to be conducted is described. The life cycle inventory analysis, involves assembling data and quantifying all inputs and outputs within the investigated system. In the life cycle assessment, the observed input and outputs are assessed to one or several environmental aspects. In the final phase, interpretation, conclusions of the study are drawn in regard to the aim of the study (Klöpffer & Grahl 2014).

3.2.1 Goal and Scope Definition

The aim of the LCA was to assess the carbon footprint of different waste management options for food waste and plastic packaging and subsequently estimate the potential of saving greenhouse gases. The study was conducted to provide information about the carbon footprint of waste and thus try to motivate consumers to sort their waste better.

For each fraction two different waste management options were compared. For plastic packaging the investigated systems were incineration and recycling and for food waste the investigated systems were incineration and anaerobic digestion. These systems were chosen because it represents the treatment of the material when it is put in the container for residual waste respectively the proper container according to VafabMiljö's sorting guide(VafabMiljö 2019).

To estimate the climate impact, attributional life cycle assessment (ALCA) was used. This method was chosen because it allows to assess the environmental burdens that belong to a product or in this study a treatment method the way it is operating today, without making any changes to it. The result of this type of LCA also provides a more conservative result compared to consequential life cycle assessment (Ekvall 2019), which may be beneficial since it will be communicated to consumers.

Functional Unit

The functional unit describes the delivered utility of the investigated system and involves a quantitative description. Emissions are subsequently specified in regard to that functional unit. For example for driving a car, the functional unit may be transport of one person one kilometer or for production of a bottle, the functional unit may be storage of one liter of liquid in 100 days (Klöpffer & Grahl 2014). In this study, the function of the investigated systems were defined as treatment of one tonne of waste and the creation of co-products from the treatment of one tonne of waste (for food waste: 2650 kWh heat, 712 kWh of electricity, 85 kWh of cool, 1020 kWh of fuel and 1.3 tonne of fertiliser and for plastic packaging: 2650 kWh heat, 712 kWh of electricity, 85 kWh of cool and 280 or 400 kg of polymer resin depending on the recycling rate used).

System Boundaries

The system boundaries define what processes are included in the analysis and what processes are not, limitations in regard to geography and time horizon can also be specified (ibid.). In this study, the system boundaries were chosen in regard to the aim of the study and following that, the study only investigated the emissions caused by the end-of-life stage for the waste. For plastic packaging this implies that all emissions caused by production and conversion of polymers were excluded. For food waste all emissions caused by production of the food were excluded. Furthermore, emissions from the usage phase was excluded. To take into account the generated co-products (electricity, heat, recycled polymer resin, fuel and fertiliser) system expansion was used. The study neither includes production or maintenance of infrastructure and capital goods.

A visual interpretation of the investigated systems and their associated system boundaries is provided below (see figure 5-7). Inputs is illustrated in yellow and include the waste, fuel, electricity and heat. In green, the waste management processes can be observed which include collection, sorting and treatment of the waste. Ultimately, outputs from the systems is depicted in blue and include biogas, biofertiliser, district heat and cooling, and recycled plastic granulate.

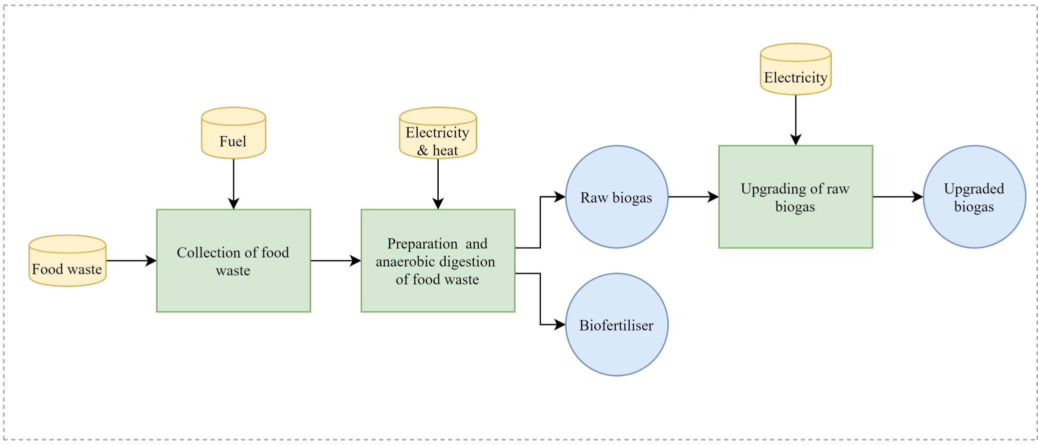

Figure 5: *Process chart illustrating the treatment of food waste where yellow cylinders depict consumed resources, green boxes represent greenhouse gas emitting processes, blue circles represent produced resources and the dotted line show the system boundaries*

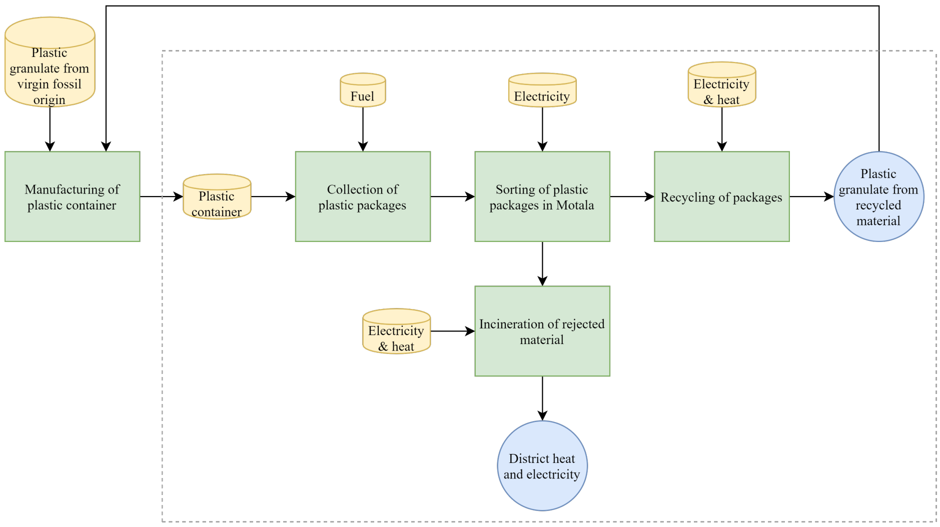

Figure 6: *Process chart illustrating the treatment of plastic containers where yellow cylinders depict consumed resources, green boxes represent greenhouse gas emitting processes, blue circles represent produced resources and the dotted line show the system boundaries*

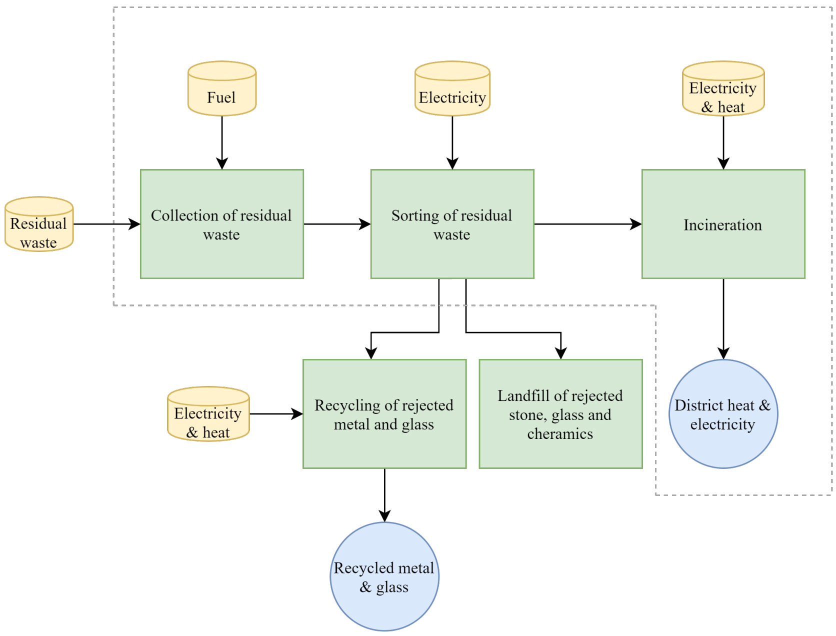

Figure 7: *Process chart illustrating the incineration process where yellow cylinders depict consumed resources, green boxes represent greenhouse gas emitting processes, blue circles represent produced resources and the dotted line show the system boundaries*

With respect to the geographical system boundary, both incineration and anaerobic digestion is assumed to take place in Västerås. Therefore, the data used for resource consumption and produced goods of the waste treatment were collected from VafabMiljö's biogas facility at Gryta waste treatment plant and Mälarenergi's incineration plant in Västerås. However, all greenhouse gas emissions produced will have a global effect, due to the nature of the atmosphere. For emissions from the recycling of plastic packaging, data from the US was gathered. However, as already mentioned, the plastic packaging from Sweden is recycled within Europe. In respect to the time horizon, average data for incineration and anaerobic digestion was collected for 2019. The choice of year, has an affect on the resource consumption and production because of impact from the weather. The choice to use data from 2019 was motivated with the comparatively low deviation in degree-days compared to a normal year and adjacent years (Mälarenergi n.d.[b]).

Co-products and Allocation Methods

Sometimes in a LCA, issues arise on how to allocate the environmental burden from a system. In this study, choices needed to be made for allocation between the number of life cycles of a material and for allocation between different products or services provided in a system.

Recycling of a material can create different kinds of secondary raw materials. If the secondary raw material is equal to the original material and of the same quality, it is called closed loop recycling. In this type of system, the material can theoretically be recycled an infinite number of times. If the secondary raw material is a new product or of a lower quality compared to the original material, it's called open loop recycling or down-cycling(Klöpffer & Grahl 2014). The recycling of the analysed materials in this study is open loop recycling.

For open loop recycling there are two common ways to deal with allocation issues between different products and that is the cut-off method and the open-loop allocation method. Both of these methods are accepted in the ISO-standard (Franklin Associates 2018). The cut-off method (also referred to as the recycled content method) allocates all emissions from the primary production of the material to the primary usage of the material. As a result, any recycled material after the primary usage has no associated emissions from the primary production of the material. Nevertheless, the emissions related to recycling the primary material is allocated to the second material, the emissions related to recycling the second material is allocated to the third material and so on (Klöpffer & Grahl 2014)(World Resources Institute & World Business Council for Sustainable Development 2011). In the open loop recycling method all emissions from the separate life stages in every cycle of the material is summarised and divided with the number of cycles the material can go though (Franklin Associates 2018). For the plastic packaging in this study, the cut-off method was used. Since the plastic material is assumed to be of fossil origin it was considered more adequate to only investigate one life cycle of the material.

Incineration provides several services: it creates electricity, heat and destructs the waste. According to guidelines from Avfall Sverige, economic allocation is recommended with a share of 58.7 % of the emissions to the energy production and 41.3 % of the emissions to the waste treatment (Dotzauer et al. 2014). Two approaches were used in the analysis for energy production, an allocation factor of 58.7 % and another one of 100 % allocation of the emissions.

3.2.2 Alternative Production of Co-products

The different waste treatment options produce several separate co-products. To enable a comparison between two systems they need to generate the same benefits. Therefore, alternative ways to produce these co-products and their associated climate impact needed to be identified and added for the different treatment options. For example, incineration produces electricity, heat and cooling. When incineration is compared to anaerobic digestion or recycling, emissions caused by alternative production of these co-products need to be added to the anaerobic digestion- or recycling system. Anaerobic digestion on the other hand, produces biogas and biofertiliser and in the same way, emissions from alternative production of these co-products need to be added to the incineration system. By recycling, polymer resin is produced and in the same way, alternative production of this co-product need to be added to the incineration system in the comparison between recycling and incineration. Figure 8 below provides a visual explanation of this.

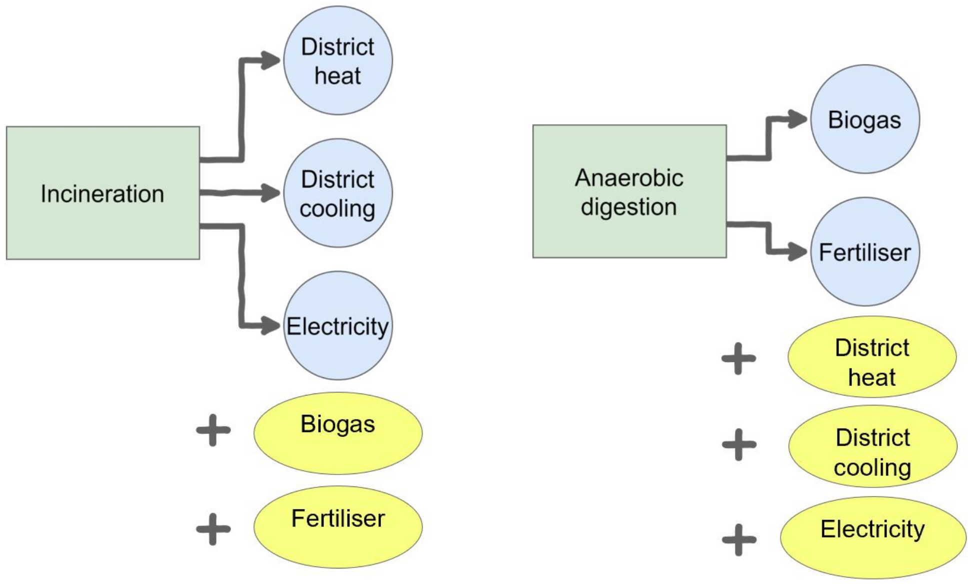

Figure 8: *A visual explanation of the system expansion for food waste where the blue circles represent co-products provided by the investigated waste treatment system and the yellow ellipses represent products that need to be externally produced to provide the same benefit as the comparing system*

The ways to produce these alternative products are described and motivated below and the data used can be found in Appendix A: Data Used in the LCA.

Electricity

In Sweden, the electricity grid is national and therefore the Swedish grid mix needed to be considered. In truth, the electricity grid is also connected to other Nordic countries in addition to a few other northern European countries. But since the Swedish electricity production has a considerable lower climate impact it was not considered fair to compare with anything else than the Swedish grid mix for the alternative system. However, import and export of electricity was taken into account.

Heat and Cool

The heat system differs from the electricity grid and it is not connected throughout Sweden. Instead it varies from city to city. In Sweden in general, district heating is a common method to heat houses and this is also true for Västerås (Mälarenergi n.d.[c]). For alternative production of heat, the climate impact resulting from the fuel mix at the incineration plant in Västerås was used. District cooling follows the same motivation and data regarding the climate impact was also collected from Mälarenergi.

Fuel
Upgraded biogas is used to fuel gas vehicles. In the gas system in Sweden, natural gas and biogas is added to the system. Therefore, natural gas will be used as an alternative production of fuel for vehicles. It is also common for gas vehicles to have an additional fuel alternative and that is normally gasoline (Miljöfordon 2017). Not only the emissions from production of the fossil fuels were collected but also emissions from combustion. It was considered unfair to not add these emissions as they will still be created and are of fossil origin.

Fertiliser
Mineral fertiliser was chosen for the alternative production of fertiliser. The biofertiliser contain less inorganic nitrogen compared to mineral fertiliser and therefore the climate impact was calculated both per mass of inorganic nitrogen but also per mass of total nitrogen. For phosphorous and potassium the climate impact were calculated per mass of the nutrient's total content. Emissions associated with the production of mineral fertiliser is described in Appendix A: Data Used in the LCA (Börjesson, Tufvesson & Lantz 2010).

Polymer Resin
Alternative production of polymer resin was assumed to be of fossil origin. This assumption can be justified by the fact that the global production of bioplastics only constituted for about one percentage of the total plastic production in 2019 and the remaining plastics were made from fossil origin (European Bioplastics n.d.). The required quantities of polymer resin from fossil origin were assumed to be 80 % of the recycled polymer resin, similar to what other studies have used (Zheng & Suh 2019).

3.2.3 Inventory Analysis and Impact Assessment

Input and output data for the anaerobic digestion system and the incineration system can be found in section 2.2.1 and in section 2.2.3. For recycling of plastic packaging emission data can be seen in figure 5. The recycling emissions include emissions from collection of the waste, transportation to a sorting facility where sorting and separation of the waste occurs and ultimately the actual recycling.

Table 5: *Emission data for recycling of one tonne of polymer resin (calculated with GWP100a and AR5-values) as well as pureness of the recycled polymers (Franklin Associates 2018)*

Polymer type	Recycling emissions	Polymer pureness
PET	910 kg CO_2e	85 %
HDPE	560 kg CO_2e	83 %
PP	530 kg CO_2e	85 %
L/LLDPE	667 kg CO_2e*	-

* Calculated mean value of the other polymers

To determine the climate impact, global warming potentials with a time horizon of 100 years (GWP100a) were used. Individual GWPs describe a greenhouse gas' ability to warm the Earth over a given period of time and in relation to the warming potential of CO_2 (United States Environmental Protection Agency n.d.). The contribution from all greenhouse gases make up the total global warming potential (see equation 2)(Klöpffer & Grahl 2014).

$$GWP = \sum_i (m_i \times GWP_i) \tag{2}$$

where
m_i=the mass of an individual greenhouse gas,
GWP_i= the global warming potential of an individual greenhouse gas

To calculate the total climate impact for each waste treatment method, the different greenhouse gas emitting processes were considered (see figure 5-7). In general those were: transport of collected waste, treatment of waste, and alternative and external production of co-products. For some processes, the climate impact were calculated by multiplying emission quantities with its GWP (as described in equation 2 and for some processes, data of the climate impact were collected from other studies. The greenhouse gases CO_2, CH_4 and N_2O were investigated in this study and the GWP_i for each gas was collected from the third to the fifth assessment report of IPCC (Forster et al. 2007; Gode et al. 2011; Myhre et al. 2013).

For the emissions caused by transport with heavy trucks, the Excel tool *Beräkning av klimatutsläpp från tjänsteresor och övrig bränsleanvändning* from the Swedish Environmental Protection Agency (SEPA) was used (Naturvårdsverket 2019b). More details about data used to calculate emissions from transport can be found in Appendix A: Data Used in the LCA. Data to calculate emissions caused by the waste treatment of food waste and the incineration of plastic packages, originating from direct emissions and the consumption of heat and electricity, can be found in section 2.2 and in Appendix A: Data Used in the LCA. Data regarding collection and recycling of plastic packages was assembled and can be found in table 5 above. For the recycling of plastic packages in Sweden, two recycling rates were investigated (50 % and 35 %). The assumed composition of the plastic packages can be found in section 2.2.2. The rejected plastic packages are incinerated in Västerås. Because of the large quantities of rejected plastics, the transport and incineration emissions from these were included as well as the produced energy from the incineration of the rejected material. External and alternative production of co-products can be found in Appendix A: Data Used in the LCA.

To communicate the climate reductions in a more accessible way, they were transformed into the equivalent climate impact from other activities: driving x laps around the Earth in a gasoline-fuelled car and flying y times back and forth Sweden–Thailand. These activities were chosen as activities considered more easily comprehensible to the general public. To calculate the emissions caused by driving around the Earth with a gasoline-fuelled car, the tool *Beräkning av klimatutsläpp från tjänsteresor och övrig bränsleanvändning* from SEPA was used (Naturvårdsverket 2019b). To calculate the emissions of flying back and forth to Thailand, a tool from the International Civil Aviation Organization (an agency of the United Nations) was used. This tool does not take into account the effects of flying at high altitudes (International Civil Aviation Organization n.d.), where the actual emissions becomes greater (Transportstyrelsen 2019).

4 Results

4.1 Waste Composition Analysis

At the start of the project, community bin A and D were considered poorly functioning, and B and C were considered well functioning. The waste composition analysis did not however reveal any significant differences in the composition of the residual waste between the different areas (see figure 9). However, there were small differences and they can be more easily identified when observing figure 10. The result indicated that community bin A and D may contain a larger proportion of packages and a smaller proportion of other residual waste. The uncertainties of the percentages, associated with the accurateness of the scale, presented in figure 9 was under 1 % for all fractions and community bins investigated. Other possible sources of uncertainties, which may be more significant, were not quantified.

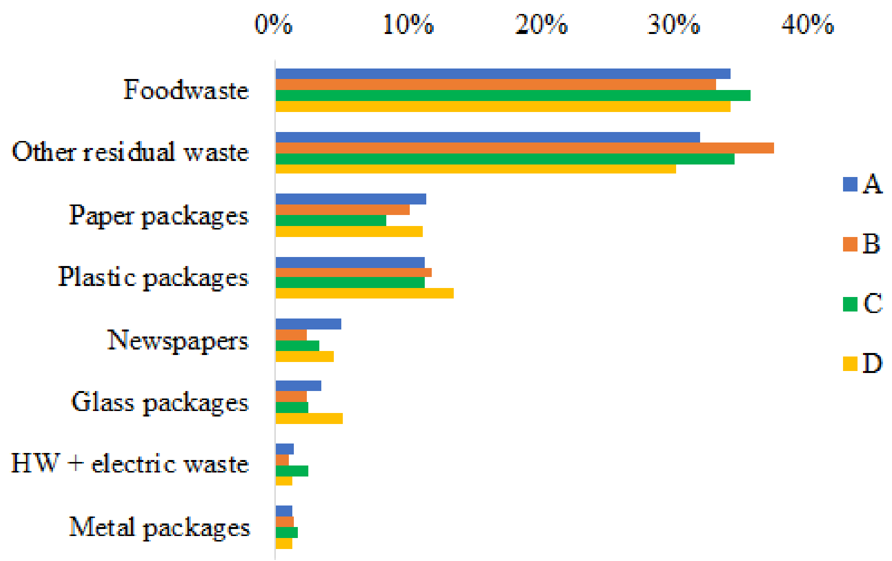

Figure 9: *Composition of the analysed residual waste from the individual areas A-D with the uncertainty of under 1 % for all fractions and specified in wetweight-%*

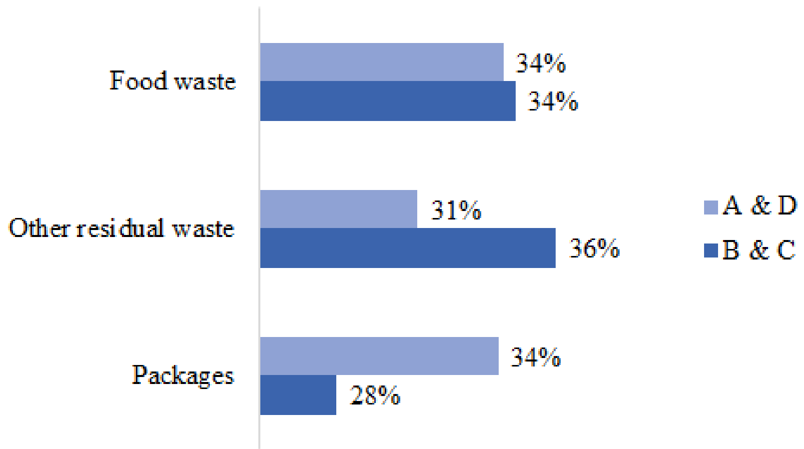

Figure 10: *Composition of the analysed residual waste where area A & D are presented together and B & C are presented together specified in wetweight-%*

Investigating the waste quantities of the residual waste, community bin A stood out from the others (see table 6). The specific community bin generated considerably more residual waste per individual compared to the other community bins. The mean value of the waste quantity of the residual waste was calculated to 175 kg per year and individual. In comparison, weight of community bin A was 246 kg per year and individual.

Table 6: *Residual waste quantities per year and individual for the separate investigated areas as well as a mean value of the generated quantities*

	Wetweight
A	246 kg
B	140 kg
C	162 kg
D	150 kg
Mean	175 kg

Due to the small variation in the composition between the different community bins, the mean composition for all community bins were calculated, as shown in figure 11.

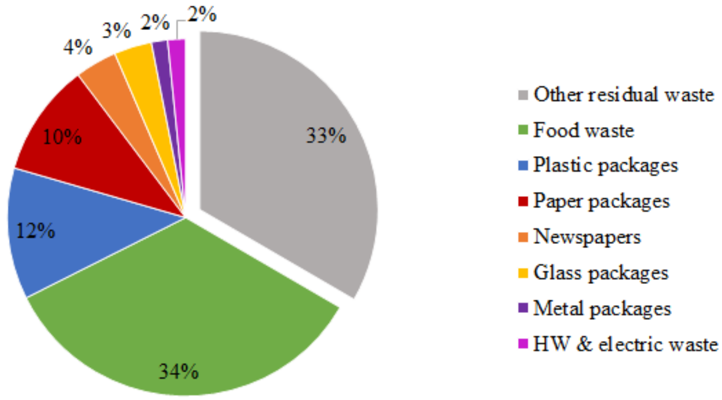

Figure 11: *Mean composition of the analysed residual waste from all investigated areas specified in wetweight-%*

The mean residual waste consisted of 33 % of materials that were correctly sorted residual waste and 67 % of wrongly sorted materials, as shown in figure 11. The contribution from packages and newspapers were 31 %, the contribution from food waste were 34 % and the contribution from hazardous- and electric waste were 2 %. Packaging and newspapers could have been treated differently in accordance with the waste hierarchy and the hazardous and electric waste, should have been treated differently to avoid adverse environmental impacts.

The number of unavoidable plastic packages estimated during the WCA accounted for 31 % with an uncertainty of 4 % due to the scale) of the plastic packages for area D and this is assumed to be true for all investigated areas.

4.2 Life Cycle Analysis of Climate Impact

4.2.1 Food Waste

Life cycle analysis of the food waste showed that anaerobic digestion cause a smaller carbon footprint than incineration for all investigated circumstances. However, the magnitude of the climate savings depend upon the chosen input parameters. With the most conservative parameters, anaerobic digestion saves more than 400 kg of carbon dioxide per tonne of food waste (see figure 12). The climate impact is divided into direct emissions from the waste treatment and emissions caused by external production of the co-products: electricity, heat, cool and polymer resin.

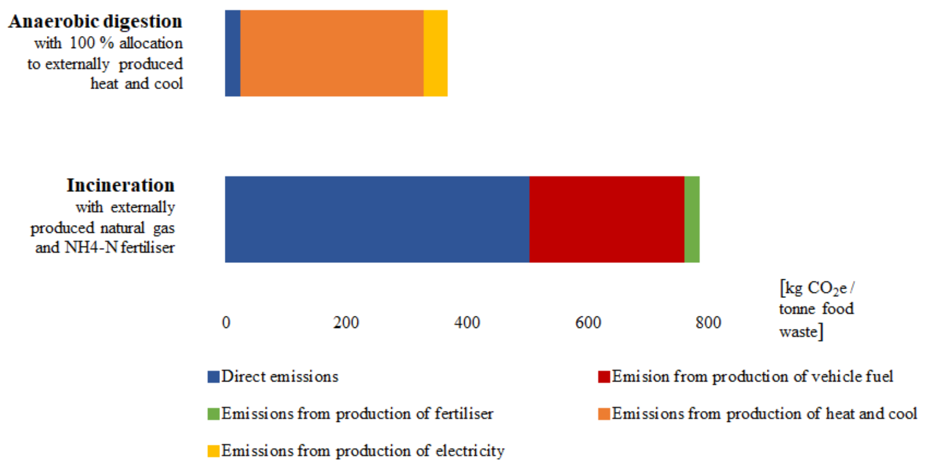

Figure 12: *Climate impact from the treatment of food waste in addition to external production of co-products, expressed in kg CO_2e/tonne food waste*

Analysing figure 12, it is clear that the external production of co-products to a very large extent determines the carbon footprint of the anaerobic digestion. In contrast, the emissions generated by the incineration mainly originate from direct emissions from the waste treatment. To investigate the impact of choices related to the alternative system, a sensitivity analysis were conducted (see figure 13).

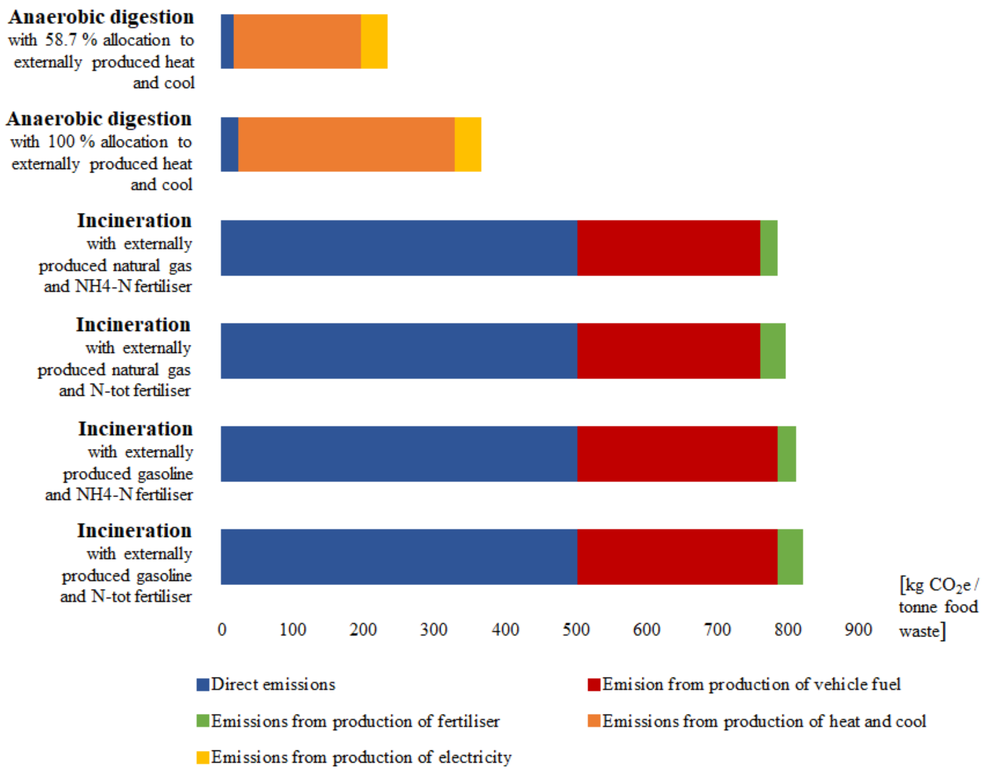

Figure 13: *Sensitivity analysis of different waste management options and different input parameters, expressed in kg CO_2e/tonne food waste*

The analysis revealed that neither the choice of vehicle fuel nor the choice of fertiliser quantity had any significant impact on the result of the carbon footprint described in figure 12. The only investigated parameter that affected the result of the life cycle analysis was the allocation factor but not to the point where it would make anaerobic digestion worse than incineration.

4.2.2 Plastic Packaging

The result of the life cycle analysis showed that material recycling of the plastics cause a smaller carbon footprint than incineration for all of the investigated input parameters. With the most conservative chosen parameters, figure 14 illustrates that recycling saves more than 400 kg of carbon dioxide per tonne of plastic packaging.

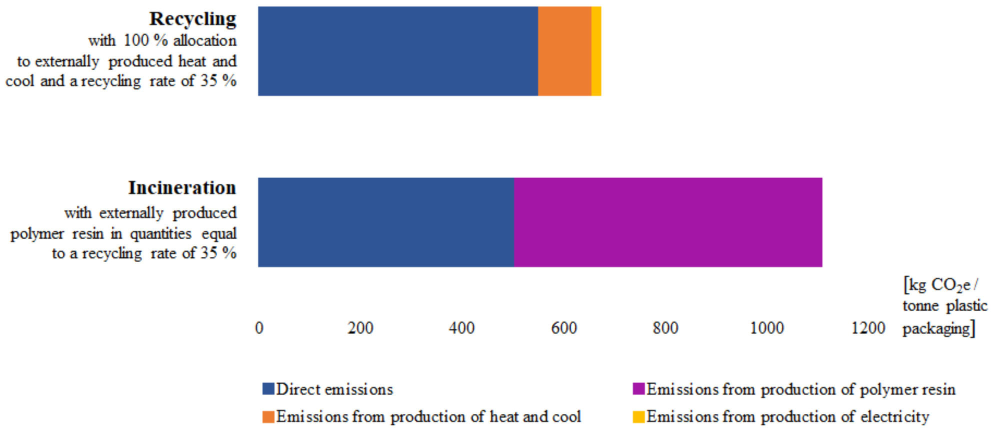

Figure 14: *Climate impact from the treatment of plastic packaging with the composition described earlier in this report, expressed in kg CO_2e/tonne plastic packaging*

Due to the uncertainty of the recycling rate and the subjectivity in the choice of some of the input parameters, a sensitivity analysis was made. In the analysis, the effect of the chosen allocation factor as well as the recycling rate can be observed (see figure 15).

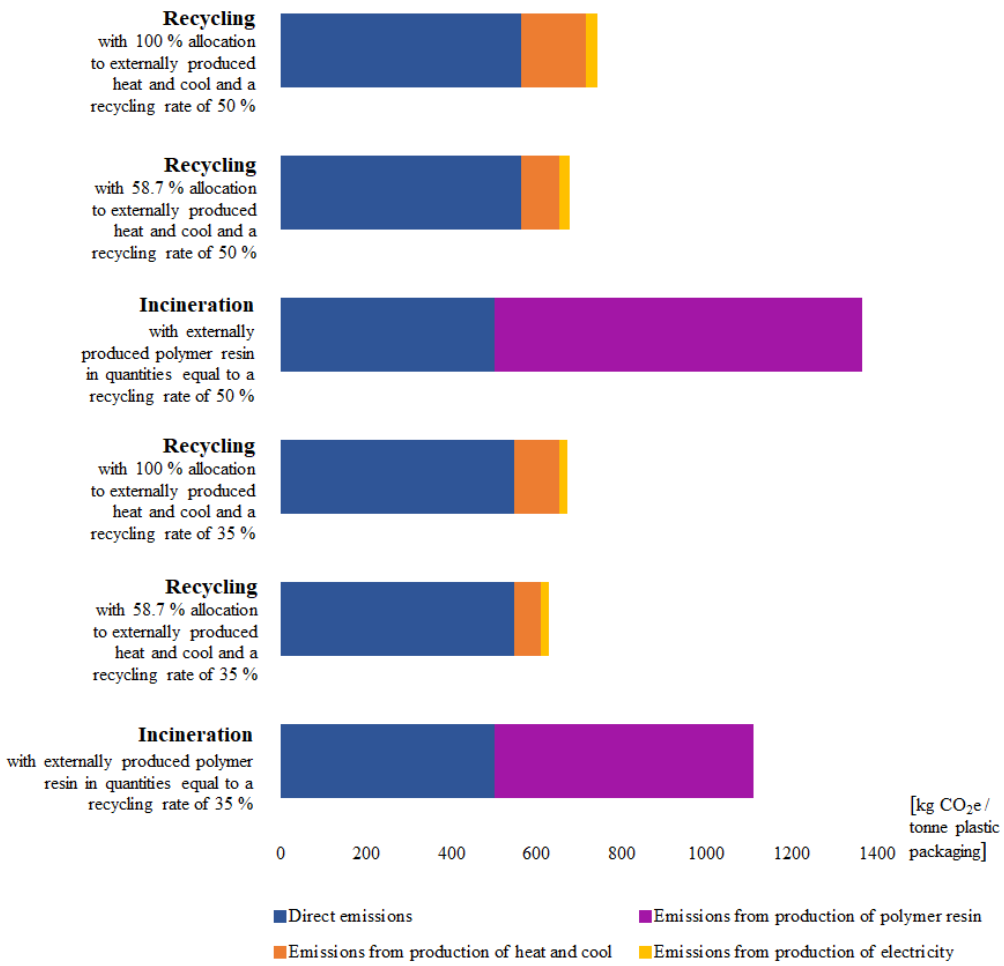

Figure 15: *Sensitivity analysis of plastic packaging waste, expressed in kg CO_2e/tonne plastic packaging*

It is clear in figure 15 that most emissions from recycling is generated by direct emissions from the waste treatment whereas for incineration a greater part of the emissions are generated by external production of co-products. The production of heat and polymer resin were identified as sensitive parameters for the outcome of the analysis.

4.3 Potential of Reducing the Carbon Footprint

In this section, results from the WCA were combined with results from the LCA to acquire results of the potential to reduce the carbon footprint through an improved sorting. Two different waste quantities and waste compositions were used to evaluate the possibility to decrease emissions of greenhouse gases. The quantity of residual waste in the first analysed case is 174 kg per year and individual which is a mean value from the conducted WCA of the investigated area. The composition of the first case is described earlier in the results. The quantity in the second case is 231 kg per year and individual which is a national average of the quantities of residual waste in 2018 and the composition of the national average (Avfall Sverige 2019a)(Leander, Zeidlitz & Åberg 2016). The possible reductions in carbon footprint was calculated for the two cases (see table 7).

Table 7: *Climate impact savings per year and individual when the most favourable waste treatment method is used compared to incineration of the waste*

	Conducted WCA	National average
Food waste	25.0 kg CO_2e	33.1 kg CO_2e
Plastic packaging	9.1 kg CO_2e	12.0 kg CO_2e
Preventable plastic packaging	6.3 kg CO_2e	8.3 kg CO_2e

If all of the residents where VafabMiljö collects their waste is included, the total climate savings per year would be 8 263 tonnes of CO_2e for food waste and 2 070 tonnes of CO_2e for preventable plastic packaging waste for the first case and for the second case, 10 910 tonnes of CO_2e for food waste and 2 733 tonnes of CO_2e for preventable plastic packaging waste. These savings would help contribute to reaching the companies environmental goals. For case 1, the total potential climate savings are equivalent to 14 900 round trips Stockholm, Sweden - Phuket, Thailand every year, meaning 4.5 % of the residents in the area can have a climate free trip every 22nd year just by sorting their food waste and plastics correctly. The savings are also equivalent to driving 1 250 laps around the Earth in a gasoline-fuelled car.

To communicate the climate impact and thus try to improve the sorting behaviour among individuals, proposal of informational material were designed by Isabella Viman (see Appendix B: Material for Communication to Individuals).

5 Discussion

5.1 Waste Composition Analysis

As expected a large extent, 65 %, of the investigated residual waste consisted of packages and food waste that could have been recycled. As illustrated in figure 11, these wrongly sorted materials were made up of 31 % packages and newspapers and 34 % food waste. As was shown in figure 9, the composition of the residual waste was similar for all investigated community bins. However, small differences were observed in the content of residual waste and packages, shown in figure 10, indicating that community bin A and D put more packaging material and less residual waste in the fraction of residual waste.

The result of the conducted WCA is similar compared to other analyses that has been executed but some differences can be noticed (see table 8 (Bergh, Boldt & Lindfors 2010; Leander, Zeidlitz & Åberg 2016).

Table 8: *Results from the analysis conducted in this study (below called WCA 2020) compared to the results from other conducted waste composition analyses*

	WCA 2020	WCA 2010	National average	
Wrongly sorted	67	60	66	%
Food waste	34	25	29	%
Packages & newspapers	31	34	37	%
Waste quantities	175	237 *	246	$\frac{kg}{year \cdot individual}$

* Calculated mean value of the municipalities investigated where a great variance in the waste quantities were observed

Earlier WCA conducted in VafabMiljö's collecting area in 2010, concluded that on average 60 % of the residual waste from multifamily-residential was wrongly sorted. This proportion is lower than the results found in the WCA 2020, but in the same order. Of the wrongly sorted materials, 34 % consisted of packages and newspapers and 25 % were food waste (Bergh, Boldt & Lindfors 2010). The proportion of packages is about the same, but the part from food waste is considerably lower compared to the WCA 2020. According to Avfall Sverige the composition of the residual waste in 2011 and 2016 is relatively unchanged, so changes over time can not explain the difference in food waste (Leander, Zeidlitz & Åberg 2016). A national review of conducted analyses in 2013-2016 show that on average 66 % were wrongly sorted, where 37 % were packages and newspapers and 29 % were food waste (ibid.). Also in this study, a higher proportion of packages and a lower proportion of food waste can be observed. These other studies indicate that the WCA 2020 to some degree may be overestimating the proportion of food waste and underestimating the amount of packages.

In contrast to the composition of the analysed waste, the waste quantities differed more between the different community bins, illustrated in table 6. Three of the investigated community bins (B, C and D) generated about the same quantity of residual waste but community bin A generated significantly more residual waste. This difference may be explained by a significantly poorer sorting, where less material is put in the recycling fractions, but it is then unexpected that the composition of the residual waste is so similar compared to the other community bins. Compared to the national average in 2018, most of the community bins generate substantially smaller waste quantities. The fact that community bin A generated more similar amounts may just be a coincidence.

There are a number of uncertainties associated with the conducted WCA 2020. The biggest concern is that it does not consider the aspect of time since the analysis was only made at a single occasion. In fact, the composition of the waste and the total waste quantities may differ over time. For example weekends, holidays and the time after payday will affect the composition and the waste quantities. Another issue is that the analysis was made on a small sample size, which leads to larger influences from deviating households and community bins. Comparing the results with other studies some differences were found. The difference in the proportion of food waste and packaging, may be caused by an inaccurate representation due to the small sample size. The possibly inaccurate representation in addition to the single analysis may also explain the smaller waste quantities compared to the national average. A possible explanation for the great waste quantities from community bin A, may be that there are more individuals per household living in this area. Data about the number of persons per household could not be obtained for the individual community bins investigated. Instead average data for Hallstahammar were used.

The fraction of residual waste was the only one investigated so the study does not give any information about the composition or waste quantities assembled in the other fractions. But the separate fractions affect each other, a decrease of waste in one fraction usually means an increase in another fraction. Of this reason it may be confusing and even misleading to analyse the waste purely in one fraction.

5.2 Life Cycle Analysis of Climate Impact

The result of the life cycle analysis showed that material recycling of the plastics cause a smaller carbon footprint than incineration for all of the investigated input parameters. In other words, the study confirms the priority order stated in the waste hierarchy in regard to the climate impact. However, the magnitude of the reductions in climate impact is affected by the choices made for the input parameters and vary between 418-588 kg CO_2e per tonne food waste and 435-687 kg CO_2e per tonne plastic packaging (see figure 13 and figure 15).

There are different approaches that can be used to present the result from system expansion. To make a fair comparison between two systems, they need to generate the same benefits. If that is not the case, the burden from external production of that benefit can be either subtracted from that same system (allowing the net emissions to be negative) or added to the compared system. Regardless of the approach, the difference between the two systems will be equal. In the conducted study, the burden from external production has been added to the compared system. That choice was made, because it allowed for an easy way to present the contribution from direct emissions and emissions from externally produced goods.

In a study by IVL, the climate impact of different waste fractions and treatment options were investigated and it showed that incineration of residual waste generates 200 kg of CO_2e per tonne of waste, anaerobic treatment of food waste generates -100 kg of CO_2e per tonne of waste and recycling of plastics generates -600 kg of CO_2e per tonne of waste (Miliute-Plepiene et al. 2019). So, the savings of greenhouse gases for anaerobic treatment of food waste instead of incineration is 300 kg of CO_2e per tonne of waste and the savings for material recycling of plastic packaging instead of incineration is 800 kg of CO_2e per tonne of waste. These results show that recycling generates a smaller carbon footprint than incineration. However, the size of the savings in greenhouse gases is pretty dissimilar from my study. There are several things that may explain the difference. In terms of the plastic packaging, the savings of greenhouse gases are larger in the results from IVL. This is most likely due to the assumed recycling rate as the recycling rate has a big impact of the result. IVL have assumed that 75 % of the packaging is recycled while my study investigated recycling rates of 35 % and 50 %.

In a LCA there are many choices that need to be made. For example choices related to the external production of the produced goods. A great variety of choices can be justified depending on the perspective and aim of the analysis, but these different choices affect the result of the study and need to be considered (Bernstad Saraiva Schott, Wenzel & La Cour Jansen 2016). In the sensitivity analyses (see section 4.2.2), parameters that had a significant influence of the result were identified. For the treatment of plastic packaging, polymer resin production and thus choices related to the recycling rate had a great impact on the result. For food waste, production of heat and cool and choices related to the allocation of these as well as the external production and combustion of vehicle fuel had the largest impact on the result.

The externally produced heat and cool are assumed to be created by Mälarenergi's general fuel-mix. The incineration provides several services: it creates electricity, heat and destructs the waste. The question is how to allocate the emissions from the incineration between these services and thus how much emissions to add to the comparing system. One could argue that the main function of the system is to destruct the waste but one could also argue that the main function is to generate energy. Avfall Sverige provides guidelines where both services are allocated a certain part of the emissions(Dotzauer et al. 2014). In this study, two approaches were investigated where the energy was allocated 58.7 % and 100 % of the emissions. For materials that can not be recycled, incineration facilities provide a great service as useful energy is produced. So for the actual residual waste one could also argue that the energy produced should not be allocated any burden of the emissions. This scenario was however not investigated, as the residual waste analysed included great amount of materials that could be recycled.

External production of polymer resin generates large amounts of greenhouse gases. Therefore the assumed recycling rate has a great impact on the result. However, the actual recycling rate is unclear. There are different estimates of the recycling rate and the most updated estimates are lower than the ones made a few years ago. There are obstacles both in collection, sorting and treatment of the material. As described in section 2.2.2, a recycling rate of 35 % and 50 % were used in the calculations.

In regard to the data used there is a few issues. The emission data from recycling of plastics is collected from the United States but plastic packages from Sweden are recycled within Europe. Since the United States uses a higher degree of fossil fuels in their energy mix, the emissions for recycling is most likely slightly overestimated. In terms of the emission data from Mälarenergi's incineration plant, there are significant waste streams that is incinerated that have not been considered such as imported waste and plastic reject from the plastic sorting facility in Motala. These waste streams may affect the size of the emissions generated. Emission data for the incineration plant also contain average values for all incinerated materials in 2019. Data for the incineration plant contain average values for all incinerated materials in 2019. As a consequence the values for incineration of one tonne of food waste in this study is equal to the incineration of one tonne of plastic packages, which is not true. Plastic packaging contain more energy and will thus create more heat and electricity (41.0 MJ/kg) as well as more emissions of greenhouse gases compared to food waste (Gode et al. 2011). As a comparison the heating value of household waste is 12.2 MJ/kg (ibid.).

5.3 Potential of Reducing the Carbon Footprint

By combining information from the waste composition and quantities with its associated carbon footprint, it was clear that a great amount of greenhouse gases can be avoided.

Uncertainties in both the WCA and LCA, as described above (see section 5.1 and section 5.2), affect the result of the potential reductions of carbon footprint. There are also issues involved to this part when the result is extrapolated over VafabMiljö's entire collecting area. In the extrapolating, it is assumed that the composition and quantities of the waste investigated in the two scenarios, are the same for all individuals in the area. However, this data is only true for multi-family residential and for single family houses the composition and quantities differ slightly (Bergh, Boldt & Lindfors 2010; Leander, Zeidlitz & Åberg 2016). The results were also extrapolated for all of Sweden to be able to more easily communicate the potential climate savings but should not be seen as representative for Sweden.

The result of the carbon footprint for different waste management options describe the system the way it is operating today. As systems change, the climate impact will also change and the carbon footprint may need to be reassessed. Possible changes that can affect the systems include an increased usage of bioplastics, an increase in the recycling rate of plastics and the new biogas facility. However, the carbon footprint for recycling is so much smaller than the one for incineration so it is unlikely that incineration would cause a smaller environmental impact after changes to the system.

In this study, the carbon footprint was only investigated for food waste and plastic packages. This choice was primarily motivated by a lack of time, but the materials were also identified as the most important ones for the companies. It was further motivated by the possibility to save the most greenhouse gases because of the amounts found in the WCA and their carbon footprint according to a study by IVL (Miliute-Plepiene et al. 2019). Further studies are required to evaluate the potential reductions of carbon footprint from the other materials found in the WCA. This study only investigated the impact category climate impact. Recycling may have other adverse environmental impacts compared to incineration. So when choices are made regarding system preferences, other impact categories may need to be assessed such as acidification and eutrofication.

The calculations of equivalent climate impact expressed in driving x laps around the Earth and flying y times back and forth Sweden-Thailand also hold uncertainties. As already mentioned, the calculated climate impact for the flying does not take into account the effect of high altitudes. This means that flying to Thailand, in reality causes a larger climate impact than the calculations showed and the actual number of flying trips is lower. The size of the effect from high altitudes is debated, but it may double the actual climate impact. To avoid the issues of high altitudes, a shorter trip within Sweden could have been used, as those normally occur at a lower altitude (Transportstyrelsen 2019).

5.4 Reflections and Recommendations

There is a lack of previous studies that has evaluated measures to affect the waste composition and quantities which was the original aim of this project. Due to the pandemic COVID-19 the original aim of the project could not be fulfilled. However, I believe Isabella and I have gained valuable insights in the area.

In terms of conducting the WCA - it is good to have a clear picture beforehand what the aim of the project is. There is a manual for how to conduct waste composition analyses, but it can still be adapted to a significant degree. Looking back at the waste composition analysis conducted, it might have also been interesting to investigate more waste fractions, for example food waste, to acquire a better understanding of how different fractions affect each other. Another matter that would have been interesting to investigate is the degree of bottles and cans that could have been deposited. It would also have been interesting to sort out plastic waste carriers from more of the waste to acquire a better confidence in the contribution it makes up of all plastic packages.

Be aware of the weather and temperature if the WCA is to be conducted outdoors. In the conducted WCA there were no problems caused by this but the significance of the temperature was recognised. In the adjacent days to the analysis the temperature was around zero degrees Celsius and if the waste would have frozen it would have been difficult to separate the different materials in the waste. The cold temperature did instead bring the benefit of little smell and no larvae that were decomposing the food waste. Also remember to follow up the evaluating WCA to assess whether potential observed effects are temporary or more far-reaching. To assess this, it is recommended that further waste composition analyses are made.

In this study, mostly informational measures were investigated to affect individual behaviours. However, it may also be of interest to further investigate other types of measures. To motivate for a better sorting, incentives such as abatement of the rent may be awarded to individuals who do well. By using information technology and try to link the individual to their waste may be a future way to make people take more responsibility of their waste as well as be used for evaluation of whom is rewarded benefits. In the waste composition analyses some bags of perfectly sorted plastics and food waste were found in the residual waste. It was brought up in the interviews that it can be difficult for certain target groups, such as kids and individuals that do not have Swedish as their native language, to understand where to sort different materials in the community bins. The descriptive signs could be more dissimilar in their appearance, the text size could be larger and colors can be used in a more obvious way. Nudging can also be interesting to analyse further, by making it simpler to sort correctly and more difficult to sort the waste incorrectly. This can be made by rearranging the bins in the communal bins, so that for example residual waste is harder to reach than food waste.

6 Conclusions

As mentioned in the introduction, there is no sign of decrease in consumption, if anything, it is increasing making the question of sustainable waste management important. The investigation revealed that as much as 67% of the residual waste was wrongly sorted and did not belong in the fraction for residual waste, so there is great potential to improve the sorting degree.

Two common materials found in the residual waste were food waste and plastic packaging. By recycling these materials instead of incinerating them, considerable reductions of the carbon footprint is achievable. The study confirms the priority order stated in the waste hierarchy for carbon footprint. Recycling of the wrongly sorted plastic packaging would generate reductions of 6.3 kg CO_2e per year and individual and anaerobic digestion of the wrongly sorted food waste would generate reductions of 25 kg CO_2e per year and individual. If all of VafabMiljö's collecting area would sort out the food waste and plastic packaging from the residual waste, these households could save in total 10 333 kg CO_2e per year, equivalent to driving 1 250 laps around the Earth with a gasoline-fuelled car every year or flying 14 900 times Sweden-Thailand back and forth every year. The size of the potential climate reductions partly depended on the choices made in the life cycle analysis and choices related to external production of heat, polymer resin and vehicle fuel was observed as more influential.

Recycling of other materials in the residual waste have not been investigated in this study, but would most likely reduce the carbon footprint additionally. To determine the total climate reductions possible for optimal sorting and treatment of the residual waste further studies are needed.

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Appendices

Appendix A: Data Used in the LCA

Characterisation factors for calculation of the carbon footprint with GWP100a

	CO2	CH4	N2O	
GWP100a (2009/28/EC)	1	23	296	(Gode et al. 2011)
GWP100a (IPCC AR4)	1	25	298	(Forster et al. 2007)
GWP100a (IPCC AR5)	1	28	265	(Myhre et al. 2013)

Transport data calculated with GWP100-AR4 values

Transport with heavy truck	0.76 kg CO_2e/km	(Naturvårdsverket 2019b)
Distance Hallstahammar-Anaerobic digestion	28 km	(Eniro n.d.[a])
Distance Hallstahammar-Incineration	21 km	(Eniro n.d.[b])
Distance Motala sorting facility-Incineration	192 km	(Eniro n.d.[c])
Capacity heavy truck	10.75 tonnes*	Email: Allmiljö & VafabMiljö

* Calculated mean value of capacities given by Allmiljö and VafabMiljö who is both responsible for collecting household waste in different parts of VafabMiljö's collecting area

Data of externally produced energy calculated with GWP100-TAR-values

Electricity

Swedish electricity mix	47 g CO_2e/kWh	(Moro & Lonza 2018)

Heat and cool

Local heat-mix (100 % allocation)	112.6 g CO_2e/kWh delivered	(Mälarenergi n.d.[d])
Local heat-mix (58.7 % allocation)	66.1 g CO_2/kWh delivered	(Mälarenergi n.d.[d])
Local cool-mix (100 % allocation)	70.9 g CO_2e/kWh delivered	(Mälarenergi n.d.[e])
Local cool-mix (58.7 % allocation)	41.6 g CO_2e/kWh delivered	(Mälarenergi n.d.[e])

Data of externally produced vehicle fuel calculated with GWP100-AR4 values

Natural gas	70 g CO_2e/MJ	(Gode et al. 2011)
Gasoline (with 5 % ethanol)	77 g CO_2e/MJ	(Gode et al. 2011)
Energy content in pure methane	9.97 kWh/Nm3	(Avfall Sverige 2019c)
Methane content in upgraded biogas	98 %	Email: Olga Korneevets, VafabMiljö

Emissions caused by production of mineral fertiliser

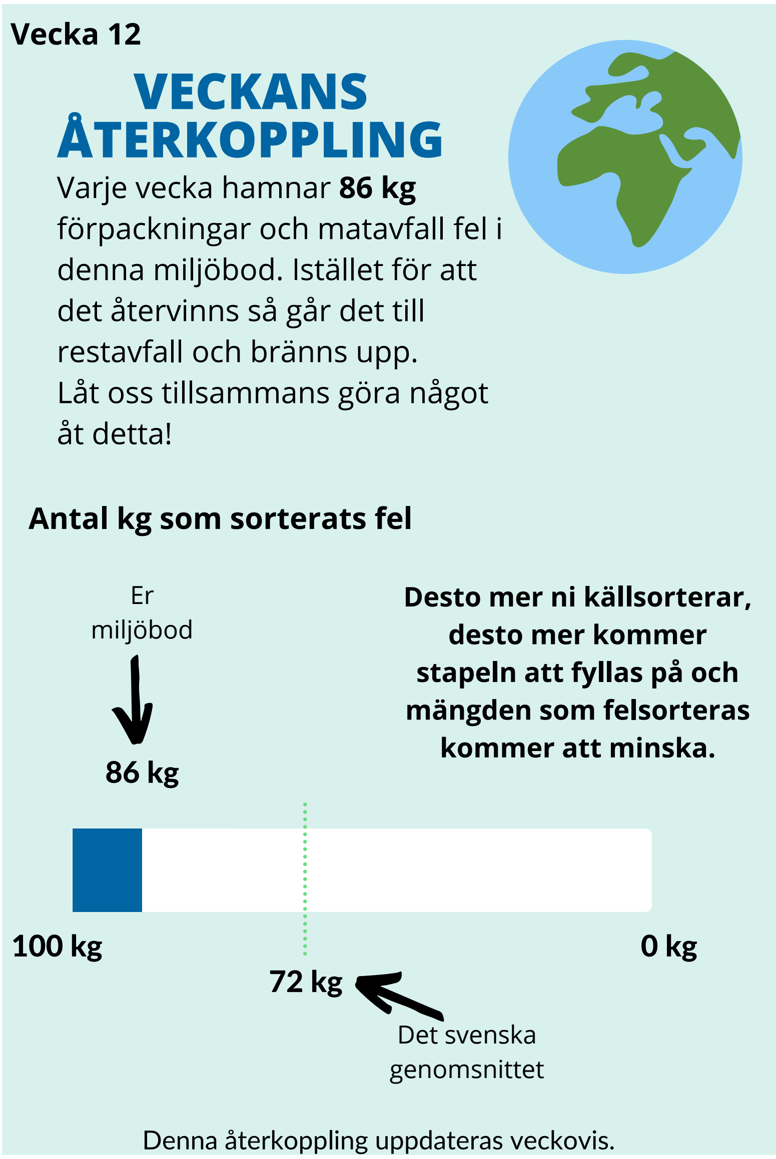
	CO_2	CH_4	N_2O	
N-fertiliser	3200 g/kg	3.1 g/kg	11.5 g/kg	(Börjesson, Tufvesson & Lantz 2010)
P-fertiliser	2900 g/kg	7.2 g/kg	0.29 g/kg	(Börjesson, Tufvesson & Lantz 2010)
K-fertiliser	440 g/kg	1.1 g/kg	0.002 g/kg	(Börjesson, Tufvesson & Lantz 2010)

Data of externally produced polymer resin

PET	3332 kg CO_2e/tonne polymer	(Zheng & Suh 2019)
HDPE	1949 kg CO_2e/tonne polymer	(Zheng & Suh 2019)
PP	1983 kg CO_2e/tonne polymer	(Zheng & Suh 2019)
LDPE	1962 kg CO_2e/tonne polymer	Mean value of the other polymers
Degree of substitution	80 %	(Zheng & Suh 2019)

Appendix B: Material for Communication to Individuals

Proposal of feedback material to be posted in community bin B. The intention with this poster is to give continuous feedback to the residents and update it once every week to try to improve their waste sorting behaviour. The information material was designed by Isabella Viman, with information collected from the conducted waste composition analysis.



Proposal of information flyer to be given to individuals sorting their waste in community bin B. The information material was designed by Isabella Viman, with information collected from the conducted waste composition analysis and life cycle analysis.

TIPS TILL DIG

Din osorterade soppåse har större påverkan på klimat och miljö än vad du tror. Även en liten förändring har en stor betydelse. Här kommer tips på hur du ska tänka när du källsorterar.

Är du osäker på hur du ska sortera en förpackning, titta på förpackningens baksida om råd. Är det fortfarande otydligt sorterar du den efter det material den består mest av.

%

En vanlig myt är att förpackningar måste rengöras noggrant, men det viktiga är att förpackningarna är tomma och behöver inte vara rengjorda.

Tack för att ni tänker på miljön och klimatet en extra gång när ni slänger ert avfall!

Under de nästkommande veckorna kommer det finnas återkoppling vid er miljöbod på hur ni har sorterat under veckan som gått. Genom att sortera ur det som kan återvinnas i restavfallet så minskar ni er klimatpåverkan och det kommer registeras och synas i återkopplingen.

Detta informationsmaterial är en del av ett examensarbete som studenter från SLU och Uppsala universitet genomför i ett projekt med Hallstahem, VafabMiljö och Mälarenergi. Detta informationsmaterial sorteras som tidning.