Master's thesis

NTNU
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Department of Energy and Process Engineering

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A Life Cycle Assessment of a waste management system introducing sorting of food waste and a central sorting facility

Master's thesis in Energy and Environmental Engineering
Supervisor: Johan Berg Pettersen
Co-supervisor: Kari-Anne Lyng
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Preface

This work compose a master's thesis in Energy and Environmental Engineering at the Norwegian University of Science and Technology (NTNU). Several greate people have been involved in the process of successfully completing this thesis, and I would like to thank my supervisor Johan Berg Pettersen for valuable inputs to my theses, my supervisor at NORSUS, Kari-Anne Lyng for steady steering and valuable conversations and thank you to Kim Rainer Mattson for helpful feedback and for cheering me on.

I would also like to thank the waste management team in Fredrikstad for letting me visit and providing me with data. Lastly, a warm thank you to my family, partner, friends and great neighbours for feedback and support during my whole master's degree.

Abstract

The EU is demanding sorting of food waste and increased recycling by sixty percent from all member states by 2030. In Norway, Fredrikstad municipality is looking for a way to meet these demands. This thesis investigates the environmental consequences of implementing food waste source sorting and a central sorting system for plastics for Fredrikstad municipality, with the aim of determining how the system flows will change and what the environmental performance of the different systems is.

To address this the waste flows were investigated to get insight in the effect of the changes implemented and to calculate the environmental impacts of the waste management system Life cycle assessment (LCA) was applied. The current waste management system of Fredrikstad was compared to one with sorting of food waste and a central sorting facility. The functional unit (FU) is set to be the handling of household waste in Fredrikstad municipality over one year. Eighteen impact categories are assessed.

It is found that the central sorting facility almost doubles the plastic sent to recycling. The environmental impact for global warming potential is better in the scenario with a central sorting facility. Yet, there is not a clear conclusion from the other impact categories of what system performs the best. The thesis ends by outlining suggested future work in the field.

Sammendrag

EU krever at alle medlemsland skal sortere matavfall og øke resirkulering til seksti prosent innen 2030. I Norge ønsker Fredrikstad kommune å finne løsninger for å nå disse målene. Denne oppgaven undersøker hva slags konsekvenser implementering av matavfall og innføring av et sentralsorteringsanlegg for plast i Fredrikstad vil ha for miljøet. Målet er å undersøke hvordan avfallsstrømmene vil endres og hva slags miljøpåvirkning renovasjonssystemet har.

For å adressere dette ble avfallsstrømmene undersøkt for å få innsikt i effekten av endringene i renovasjonssystemet og for å finne miljøpåvirkningene ble Livsløpsanalyse (LCA) brukt som metode. Det nåværende renovasjonssystemet i Fredrikstad ble sammenlignet med et system med sortering av matavfall og sentralsorteringsanlegg for plast. Den funksjonelle enheten (FU) ble satt til å være behandling av husholdningsavfall i Fredrikstad kommune over ett år. Atten påvirkningskategorier ble studert.

Resultatene viser at sentralsorteringsanlegget kan tilnærmet doble utsorteringen av plast sammenlignet med sortering hjemme hos innbyggerne. Videre har scenariet med sentralsorteringsanlegg lavere utslipp for av drivhusgasser, målt med det globale oppvarmingspotensialet. Likevel er ikke de resterende mijløpåvirkningskategoriene enstemte om hvilket scenarier som gjør det best. Oppgaven avsluttes med å foreslå videre arbeid for feltet.

Contents

1 Introduction

1.1 Background and motivation

In 2016 the amount of municipal solid waste generated was estimated to 2.01 billion tonnes by The World Bank, and they expect it to increase to 3.4 billion tonnes by 2050 (Kaza et al., 2018). Out of these tonnes of waste as much as 33 percent is openly dumped and only 19 percent will go through materials recovery by recycling and composting.

Seeing that there is a need to address these huge amounts of untreated waste the EU is introducing ambitious goals for their member states. For municipal waste the EU wants an increase of preparing for re-use and recycling to a minimum of 55 %, 60 % and 65 % (by weight) by respectively year 2025, 2030 and 2035 (The European Union, 2018). It is also demanding sorting of food waste from all member states and aim to halve the food waste per capita by 2030 (EU, 2021).

In Norway this is implemented in the "National strategy for a green, circular economy", where the country point out its goals of reduction in food waste to 30% by 2025 and 50% by 2030 (Klima- og miljødepartementet, 2021). The Norwegian municipalities that do not yet have sorting of food waste will need to find out what type of waste collection methods shall be implemented. In these municipalities food waste is today thrown in residual waste, but with the new EU goals this will have to change. When the food waste is no longer in the residual waste this opens up for a different sorting of plastic waste. Today, the most common thing in Norway is to source separate the plastic. But, when the food waste fraction don't litter the residual fraction, one can throw the plastic in the residual waste, letting this mixed waste fraction go to a central sorting facility, that will separate the plastics. This can give more plastic sorted than the average citizen and thus help Norway reach its circularity goals Klima- og miljødepartementet (2021).

Waste management is becoming increasingly complex and play an important role in achieving a circular economy (Christensen et al., 2020). Proper handling of waste is one of the key factors to achieving circular economy. On the way to getting a circular economy, municipal waste holds several keys. Key elements of circular economy, such as closing loops and extending product life cycles are directly dependent on a circular handling of material flows in the municipal waste system (Khatiwada et al., 2021). Two key elements on a country level is recycling of biowaste and the recycling rate of plastic packaging, and the recycling rate of the municipal waste in itself.

Whether the quality of a central sorting facility is better than the source separation is unclear. There are two facilities like this in Norway today. Other countries in Europe also have similar facilities, but the waste flows are often different, and there are difficult to find systematic data. Furthermore, the different demographics of the places with central sorting facilities can make the numbers available incomparable. There has been performed many LCA studies on solid waste management systems, yet the results are strongly dependent on waste composition, energy system and other local conditions which makes it difficult to draw generalisations from other LCA results (Laurent et al., 2014). No LCA has been performed yet to assess the environmental performance of such a change to the waste collection system.

This thesis will look at the changes in the waste disposal system as there is introduced separate sorting of food waste and a central sorting facility to sort the plastic waste. In theory this should remove all food waste from the residual waste fraction, but to find out how the flows will look in real life numbers from the existing central sorting system ROAF will be looked at.

This thesis will address this by investigating the waste flows and using Life Cycle Assessment (LCA) to calculate the environmental impacts of the waste management system. To get the most accurate results form the LCA there is a need to understand the flows of the system and how they change from one scenario to the other. To do this an in depth system description will be performed, using elements of Material Flow Analysis (MFA) aspects as this can be used for evaluating the performance of solid waste management (Khatiwada et al., 2021). For comparing two systems as I will do here LCA is a great tool. LCA has proved very important in waste management to help us understand the waste flows and their potential environmental impacts. Till now the method has given many results of things we today see as given, such as confirming the importance of the waste hierarchy (Christensen et al., 2020). I will try to better understand the environmental impacts of the system in Fredrikstad today, and compare it to a system with a central sorting facility. Finding out if these changes are beneficial for the system, for example giving us more or better quality plastics, so that we recycle more, will be important to know if the expensive facility is worth building and changing infrastructure for. Having an LCA of the systems could this way assist policy makers with strategic choices regarding waste management.

This paper will follow the IMRaD methodology for writing. After this introduction, the methodology will be presented. Thereafter the results will be presented and discussed. Limits, future work and recommendations will be pointed to. Lastly, the conclusion will be presented.

1.2 Objective

The objective of this thesis is to investigate what effects the alteration in the waste management system of Fredrikstad municipality, from implementing food waste source sorting and a central sorting facility, that will sort out plastic waste from the residual waste, will have on the environmental impacts of the system. For this the following main goal can be formulated:

Main goal To assess the environmental consequences of implement food waste source sorting and a central sorting system for Fredrikstad municipality

To investigate the main goal and fill the information gap on the effects of sorting food waste and implementing central sorting for increasing separation of plastic waste the following research questions, RQ, have been developed.

Research question 1 How will the system flows change?

In order to answer this an analysis on the waste flows is performed to get an in depth system description. To do this it will be helpful to base the analysis on material flow analysis principles. Read more about this in Section 2.2.

Research question 2 What is the environmental performance when altering the waste management system?

To investigate this a Life Cycle Assessment (LCA) is performed. Since the LCA is a method for comparing systems, and we will be comparing the system before, and after the changes.

The methodology for the LCA is described in Section 2.3

2 Methods

The following sections describe the method of the data collection and carrying-out of an LCA.

To comply with the research questions presented in Section 1.2 the following has been done. To solve RQ1 a case study will be put down, to be able to look at a real system.To find an answer to RQ3 an LCA will be conducted. LCA is a tool for comparative analysis, and since we are looking at a system before and after change the LCA will be suitable.

2.1 Case: Fredrikstad municipality

Fredrikstad municipality has been chosen as a case system in order to acquire a better understanding of the way a waste management system will change with the intended alterations described in the objectives of Section 1.2. The municipality needs to implement sorting of food waste, and they are planning to procure a central sorting facility for plastics.

Fredrikstad municipality is one of the bigger cities of Norway with 83 761 inhabitants (2021) and is expected to continue growing throughout the coming years (SSB, 2021). The municipality is situated in the southeast of Norway, as can be seen in Figure 1, and its total land area is 284 km^2 (Thorsnæs, 2021). A total of 93% of the inhabitants lives in densely populated areas and there are on average 2,16 residents per household. The majority of inhabitants in Fredrikstad lives in single family houses, and the ratio of single family houses to apartments is around 2.7:1 according to SSB (2021).

Fredrikstad writes in their climate plan that they by 2030 shall have reduced their greenhousegas-emissions by 60%, compared to 2016. They will further contribute to having net-zero emissions in the county Østfold. Fredrikstad further will play a part in obtaining a global low emission society by 2050 (Fredrikstad kommune, 2019).

Figure 1: Fredrikstad municipality marked with an arrow on the map. From Norgeskart.no

To be able to understand the analysis and how the alterations will affect the waste management system we need to understand how it is today in Fredrikstad and what parts it contains. The waste management of household waste in Fredrikstad today consists of the following waste types: plastics; paper, cardboard and carton; glass and metals and residual waste. It is also possible to get a home composting system for food waste. The waste types have their own collection bins, except for plastics where the inhabitants get a plastic bag that will be placed on the side of the bins on the collection day, shown in Figure 2. Plastics and paper, cardboard and carton gets collected in a two chamber vehicle with the chamber size is distributed 30/70 percent, with the biggest chamber for paper, cardboard and carton. Remaining fractions are picked up by one chamber vehicles. Today Fredrikstad both have vehicles operation on diesel and on biogas.

Figure 2: Plastic bag placed on side on bin for collection. Picture by the author.

Per year around 477 kg of household waste will be thrown per inhabitant in Fredrikstad. The material recycling degree of the city is today ca. 24 %. Parts of what is thrown today are materials and resources that could have been re-used, repaired or recycled to get them back into the loop (Fredrikstad kommune, 2019). They hope to improve this with a central sorting facility.

To construct a realistic future scenario it is important to know how Fredrikstad have projected their new municipal sorting. At present it is planned that MOVAR, and the municipalities Fredrikstad, Halden and Sarpsborg will share the central sorting facility (Eggen et al., 2020). A facility like this will receive residual waste and plastics in the same flow and the main purpose of the facility will be to separate the plastic packaging. This requires that food waste is sorted in a separate waste flow than residual waste, otherwise it will contaminate the plastics. The placement of the facility is planned to be next to the incineration plant in Fredrikstad.

It is not decided yet if other waste types, like metals or textiles also will be sorted by the facility. This will be of importance as e.g. metals are valuable and if they are sorted out and treated it will improve the environmental impact of the facility. Further there should be a focus on more separate sorting of glass and textile waste as this respectively leads to less damage and stop on the facility according to the report of (Eggen et al., 2020). It is also not decided yet if the food waste will be collected in bags thrown together with the residual waste, and then separated by near infrared technology (NIR), at the facility, or whether the food waste shall have their own waste bins. The latter is recommended by the last report for the project by NORWASTE (Eggen et al., 2020), as having a separate bin for food waste leads to dryer and higher quality on the other waste types. One reason for this is that around 30% of the bags will burst during collection, and thus contaminate the other fractions, this also leads to loss of valuable food waste into the residual waste (Bjørnerud and Hultin, 2021). There are implications that having bins for food waste will give higher amounts of sorted food waste (Lystad et al., 2020). Which method is chosen for the collection of food waste will be of importance for the modeling as the additional bins will have a climate impact. All in all, these undecided factors can influence the environmental impact of the system.

2.2 In depth system description

Now that we have got an overview of the waste management system functioning in Fredrikstad from the last section, we will investigate the system at a deeper level in this section by presenting the methodology behind the carrying-out of an in depth system description. For this we will be using elements form material flow analysis, MFA, which is a method that will be described briefly together with its relevance for waste management systems. Thereafter, the comprehensive system "waste management in Fredrikstad" will be defined. This will be followed by the definition of the two main scenarios, the system today and the system with separate food waste and a central sorting facility. Lastly the flows will be assessed.

2.2.1 System definition and scenario descriptions

MFA and waste management

Before we look at the systems it will be helpful to know how we can use elements from the method material flow analysis, MFA, in order to define our systems and scenarios and with these elements be able to answer the research questions from Section 1.2. Material flow analysis can be defined as the systematic assessment of the flows and stocks of materials within a system defined in time and space (Brunner and Rechberger, 2004). MFA uses mass balance as a main principle, which states that all inputs to the system must be equal to the outputs and stock accumulations of the system. Hence, it is a tool to analyze the goods, materials or substances in systems and how they change, move and are stored (Brunner and Rechberger, 2004). This thesis will examine the changes in material flows in a waste system when we implement a central sorting facility. Thus, using principles from MFA will be helpful as MFA is highly useful for analyzing waste management systems Allesch and Brunner (2015). Waste MFA can also be used for various objectives, for instance evaluating the performance of an existing system as well as comparing systems, such as two different treatment plants, or for system analysis, for example to give inventory data to a life cycle assessment, LCA (Allesch and Brunner, 2015). In this thesis the in depth system description using MFA elements is needed to investigate RQ1, as described in Section 1.2, and will both give us a comparative analysis on the change of the flows form the old system in contrast to the new one, as well as providing inventory data to the LCA needed to comply with RQ2.

System definition of waste management in Fredrikstad

To be able to compare the two waste management options the system which is observed must be defined. The spacial boundary of the system is set to the borders of Fredrikstad municipality and the export of waste to other countries for the recycling processes were included in the system.

The period of the study is defined to be one year, for all the processes and the flows of goods. This is natural as statistics about waste management often operate in yearly numbers. As the system input the annual amount of household waste in Fredrikstad in 2019 year was chosen because this is the last year of available data without influence of inhabitants behavioral changes due to COVID-19. This was a total of 19047 ton residual waste.

As described in Section 2.1, presently in Fredrikstad municipality the inhabitants sort their waste into four categories, namely residual waste; paper, cardboard and carton; glass and metals; and plastics. Food waste is currently thrown in residual waste, but it is possible to get a home composting system for food waste. The waste is collected by collection vehicles and sent to their respective facilities for treatment. This includes an incineration facility and recycling facilities.

With the main parts of the system, the structure of collection and sorted waste categories, mentioned in the sections above, we will look at the two scenarios: The status quo system describing how the waste management in Fredrikstad works per now, and the future scenario trying to give a most accurate description of how the new waste management in Fredrikstad will be.

Status quo scenario

In Figure 3 you can see an overview of the waste management system in Fredrikstad as it is today, as described in Section 2.1. The flows of waste are illustrated by the arrows and the boxes represent processes of waste management. The system boundary is defined as including everything except the white boxes, because, as mentioned the paper, cardboard and carton as well as glass and metals are not included as they will not be influenced by the changes performed on the system.

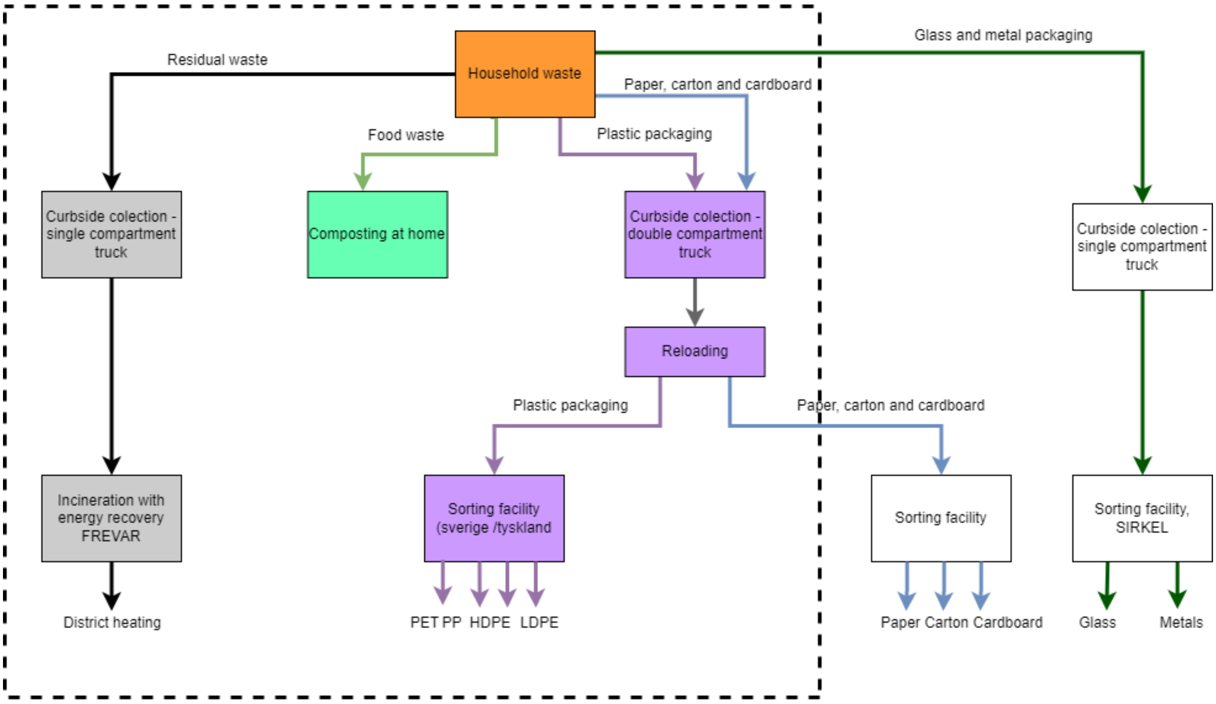


Figure 3: Waste system in Fredrikstad today

As one can see Fredrikstad today has a sorting system for the household waste where they sort plastics; paper, cardboard and carton; glass and metals and residual waste. It is also an option for the inhabitants to get a box to compost food waste at home, if not, it will be thrown in residual waste. The waste types is collected in vehicles with one or two chambers before they are sent to redistribution or directly to treatment facilities.

Future scenario

The second scenario can be seen in Figure 4 and represent the system with alterations performed to make a new waste management system in Fredrikstad. This scenario includes initiating sorting of food waste and a central sorting facility that will separate plastics from the residual waste. When the food waste is sorted at the household it will be collected and transported to a biogas facility that makes biogas for vehicles. The plastics is thrown together with the residual waste, before it will get separated again in the sorting process performed by the central sorting facility.

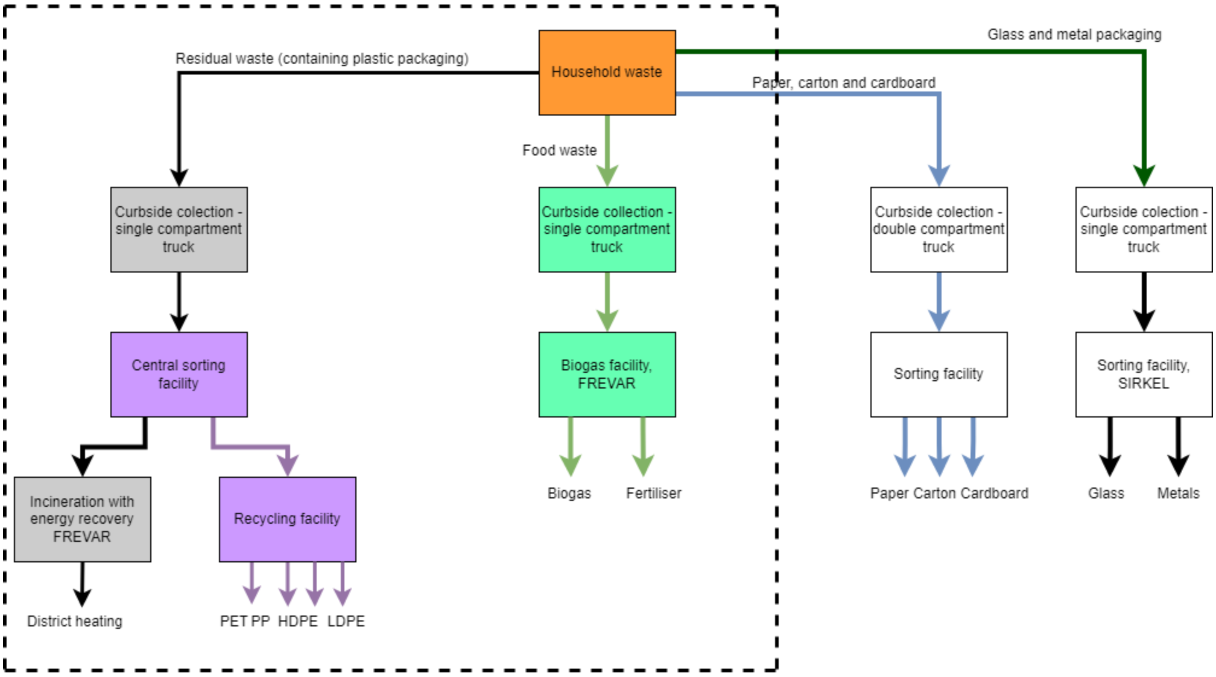


Figure 4: Waste system in Fredrikstad after the researched changes

2.2.2 Determination of material flows

The amounts measured in tonnes for the flows were found from different sources, but mainly the numbers were obtained from Fredrikstad municipality, either through official documents or from qualitative interviews.

Status quo scenario

Many of the flows in the status quo scenario was known by obtained information from Fredrikstad. The amount of residual waste per year is 19047 tons. And for plastics it is 378,2 tons. There is assumed to be no losses in the collection of the waste by the vehicles.

Residual waste:
The composition of the residual waste today can be seen in Figure 5. This information comes from an analysis performed by Mepex where they have looked at random samples of the waste of Fredrikstad in 2021 (Syversen et al., 2022). The analysis was done under a period without the societal lockdown due to COVID19, which will give numbers less affected by temporary behavioural changes due the corona virus pandemic. The analysis covered different types of dwellings, namely single family houses in both urban and rural areas of the municipality, as well as apartments and terrace houses (Syversen et al., 2022).

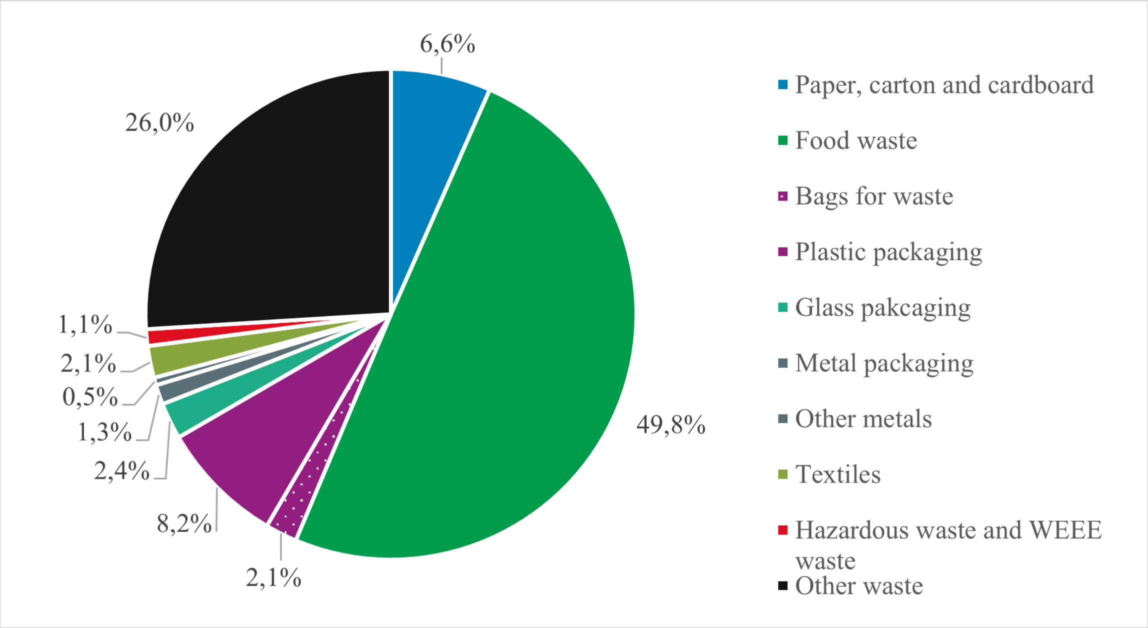


Figure 5: The composition of household residual waste today in Fredrikstad municipality. Data from Syversen et al. (2022). Colours inpired by Loop pictogram coloursystem.

From Figure 5 we can see that approximately half of the residual waste consists of food waste. Out of this 53,5% is usable food waste, meaning that it could have been eaten (Syversen et al., 2022). Examples of the "other waste" in the report is paper and cardboard not suitable for recycling, plant residues, EPS (polystyrene), glass (other types than food containers), wood, nappies and sanitary pads. A full list can be found in figure 10.3 in Bjørnerud and Hultin (2021).

There is assumed to be no losses in the collection, and therefore the 19047 tonnes of residual waste generated by the households of Fredrikstad will be the input to the incineration facility FREVAR Fredrikstad kommune - avdeling renovasjon (2022). From this waste it is produced high pressure steam and district heating.

Plastic waste:
For the plastic waste it is assumed to be no losses in the reloading. Thus, all 378,2 tonnes generated by households in Fredrikstad will be input to the Sorting facility in Germany. The composition of plastic packaging in the source separated waste can be seen in Figure 6.

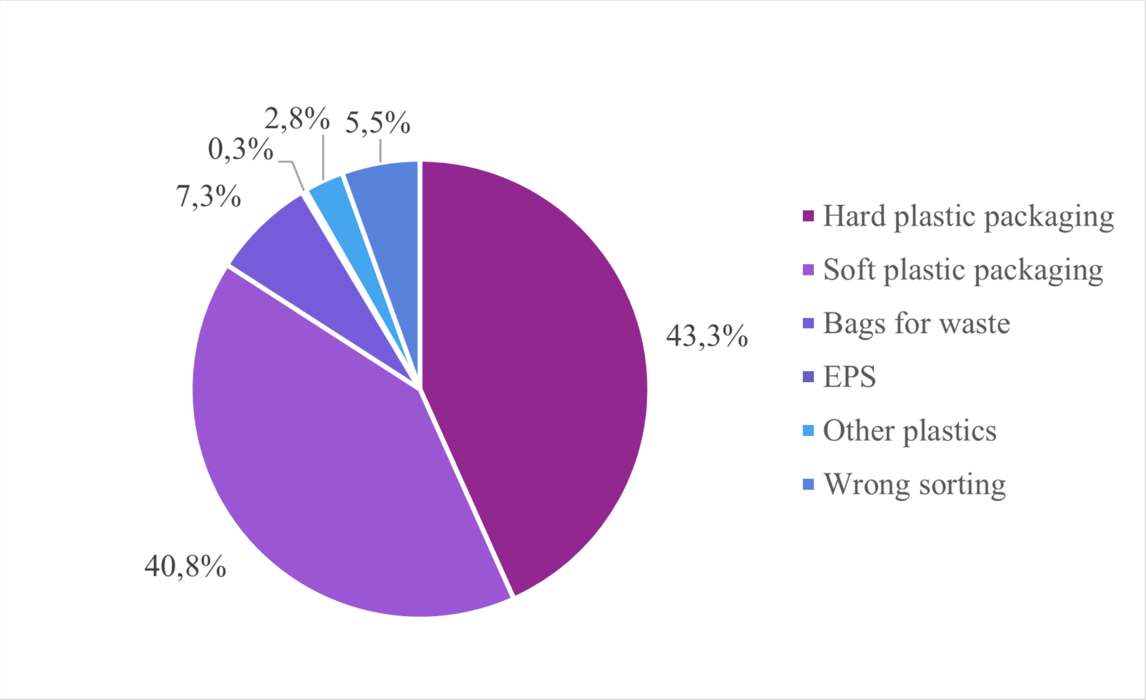


Figure 6: The composition of plastic packaging types in the plastics that have been source separated at the households. Numbers from Syversen et al. (2022).

We can see from Figure 6 that the majority of plastics are hard and soft plastics. The plastic types are further elaborated in Syversen et al. (2022) and have been summarised by the main plastic types, PET, PP, PE, foil and mixed plastics in Table 1. The mixed plastics are all other types of plastics like PVC, PLA, black plastics and PS. The percentages does not sum to 100% which is most likely either because Syversen et al. (2022) have truncated the numbers in a strange way, or that they have a small percentage of pollution that has not been included.

Table 1: Source separated waste at household content of PET, PP, PE, Foil and mixed plastics. Numbers in percentage per mass

Plastic type	Residual waste	Plastic waste
PET	13,3%	14,1%
PP	13,9%	12,5%
PE	7,5%	8,0%
Foil	55,3%	56,9%
Mixed plastics	9,5%	8,2%

Future system

For the future system, calculations and assumptions are needed to be made.

Residual waste:
In the future system two main thing will happen to the residual waste. Firstly, the plastic waste will enter the flow, as the original residual waste and the plastics is combined and go together to the central sorting facility. Secondly the food waste will diminish as the inhabitants will get a separate sorting of food waste. Nevertheless, not all of the food waste will get removed from the residual fraction, as it is safe to assume that some inhabitants will not follow the new sorting.

Food waste:
The food waste content of the residual waste was 49,8%, resulting in roughly 9485 tonnes of food waste that, in theory, can be sorted as food waste and be treated at the biogas facility. Nevertheless, it is safe to assume that some inhabitants will not follow the new sorting. The waste analysis performed at the ROAF central sorting facility in 2021 suggests that the amount of food waste in the residual waste will be 33,3% with a central sorting facility which is what will be assumed in this project.

Plastic waste:
It can be assumed that all the 378,2 tonnes of plastic packaging that today is separately sorted will enter the residual waste fraction, as the inhabitants have no other option of throwing it.

Central sorting facility:
At the central sorting facility the residual mix containing all plastic waste, and less food waste than before, will be collected as we saw in Figure 9. In the central sorting facility the residual waste will be separated from the plastic waste. Knowing how much of the plastic the facility sorts out is crucial to the efficiency of the facility. How it performs affects how much of the plastic waste will get recycled, and if this amount is bigger than the amount that the inhabitants sort out for recycling today. From ROAF numbers we know that in 2019 the facility sorted out 6,77% of all the PET, 27,32% of PP, 35,92% of PE and 40,41% of plastic film, which I will assume to be LDPE. These numbers are the percentages that will be sorted out of the composition of plastics showed in Figure 6.

2.3 Life cycle assessment, LCA

This section will explain the principles and concepts behind life cycle assessment, LCA. To understand how a life cycle assessment, LCA for waste management works we must first take a look at regular LCA.

An LCA is used to assess the main environmental impacts a product or service has created through its life cycle ISO 14040:2006 (2006), ant the method can assist in identifying where in a life cycle there is opportunity to improve the environmental performance and is especially useful when used for comparative studies. This makes LCA into a valuable tool for decision support, and it has been standardised in the standards ISO 14040 and ISO 14044.The LCA consist of 4 phases; goal and scope, inventory analysis, impact assessment and interpretation. The steps will be completed as an iterative process as can be seen in Figure 7.

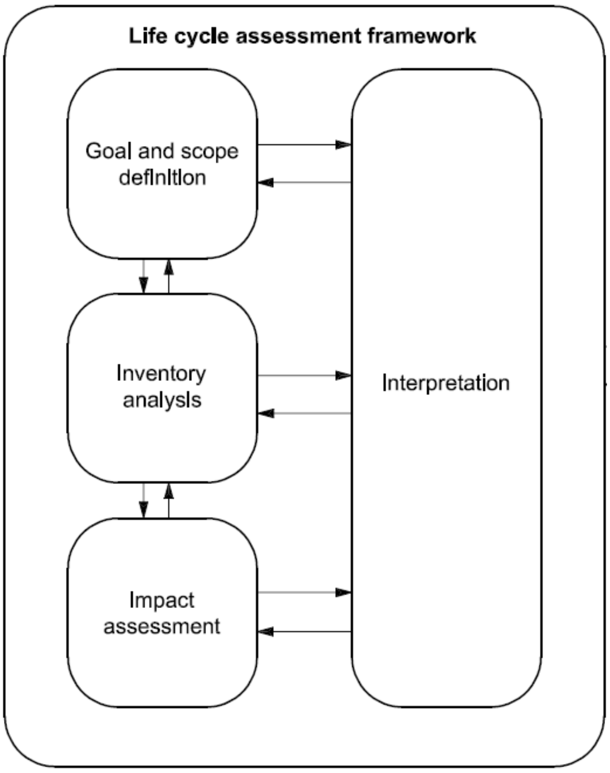


Figure 7: Stages of an LCA, from ISO 14040:2006 (2006)

2.3.1 LCA of waste management

LCA performed on waste management systems differ a bit from regular LCA because it primarily focuses on the end-of-life stage, and all other life cycle stages are excluded. In contrast the regular LCA usually focuses on the production and use stages, where waste solely will be an output of the system (Hauschild and Barlaz (2011b)). LCA performed on waste management systems is sometimes referred to as "waste LCA". The main goal of the waste LCA is to get an holistic view of the activities involved in the system, such as emissions and resource requirements, and doing this with the purpose of getting more informed decision making related to waste management (Hauschild and Barlaz, 2011a).

2.3.2 Goal and scope definition

Goal

To comply with RQ2 the goal of the LCA will be to find the environmental impact of implementing household sorting of organic waste and central sorting of plastic waste. Here the existing system in Fredrikstad will be compared to a system with the new implementations. This way we can discover differences in performance of the new system compared to the existing system, which will be important for knowing if the investment and changes that are planned to be implemented in Fredrikstad will be worth it, and if other municipalities in Norway should do the same

The reason for carrying out the LCA is to close the gap of information on the environmental impacts of implementing food waste sorting and thus enabling central sorting of plastic waste.

In Norway there is an optimism around Central sorting facilities and how they will enhance the recovery rates for material recycling, without confirmed research (Miljødirektoratet, 2019). Having performed an LCA will be valuable for decision makers who wants to get better insights into whether the environmental impacts of a waste management system with central sorting will be better than source separating plastic waste.

The results will give insight in how the environmental impacts look in the new system, and can present valuable information to policy makers working with waste management systems. This is especially important now that the EU is demanding that all member countries shall collect organic waste (The European Union, 2018).

Scope

The functional unit, FU, is set to be: The handling of household waste in Fredrikstad municipality over 1 year. As mentioned in the goal the focus of the household waste will be on the residual waste, which today includes food waste and the plastics fraction. The choice of having the time scale span across over 1 year is logical due to the fact that most statistics are presented over the course of a year. The clients of the renovation service, in this case the inhabitants of Fredrikstad, also pays for the service on a yearly basis.

A system drawing of the waste flows as they are today can be seen in Figure 8. The system boundaries includes the processes that are affected by the change in waste flows. As already mentioned in Section 2.2.1 the paper, cardboard and carton as well as glass and metals are not included as they will not be influenced by the changes performed on the system. This is because they have their own collection, which will continue unaffected. The system after introducing changes described in Section 2.2, can be seen in Figure 9.

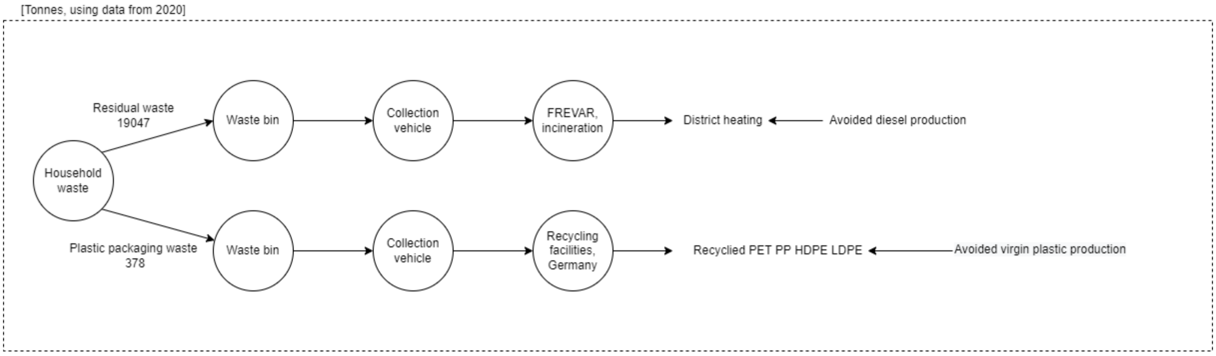


Figure 8: Waste flows with manual sorting of plastic waste and no food waste source separating

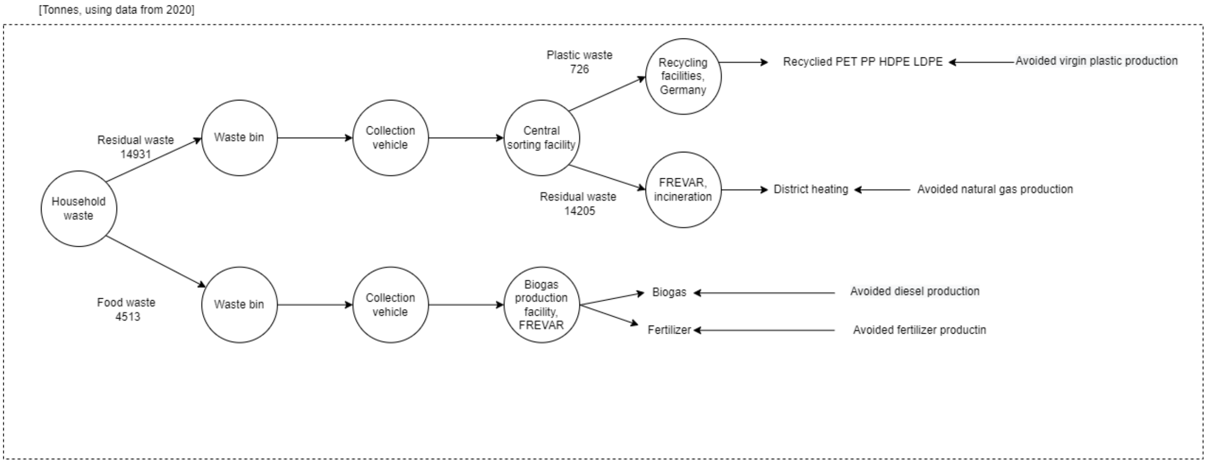


Figure 9: Waste flows with central sorting and source separate food waste sorting

2.3.3 Life cycle inventory, LCI

In the life cycle inventory, LCI phase the inventory included by the system boundaries will be presented. This include the collection and calculation of data. In this case the inventory consist of the elements and resources needed for the municipal solid waste collection in Fredrikstad, as well as the facilities for sorting and treatment as can be seen in Figure 8 for the existing system and Figure 9 for the future system.

Parts of the inventory

Waste collection bins The waste collection bins are part of Fredrikstad municipalities waste management. Thus, information such as the number of bins of different sizes were extracted from their data. The bins are from Total Holding who produce them in mainly recycled HDPE. Fredrikstad could also inform that lifetime of the bins varies depending on of the type of container. The container types they now use showed to have a slightly shorter lifetimes between 5-15 years. This depends on factors such as if they are stored indoors or outdoors and how resistant they are to the handling and the process of emptying into the vehicles. In this task the lifetime of a waste collection bin has been set to 10 years.

The weights of the different bins were obtained from Total Holding. The weights for 100L and 600L were not given explicitly, and was therefore obtained by interpolating from the bins with available data closest to the weight of the bin. When presenting the weight with one decimal certainty the calculations gives 9,7 kg as the weight of a 100L bin. For the 600L I will assume the weight to be equal to 660L.

The existing system in the manual sorting scenario has a set amount of the different sizes of waste bins, which number was given by Fredrikstad municipality. In the central sorting scenario there has been added bins for the food waste. These have been assumed to be of the same amount as the paper bins, since all inhabitants that has a paper bin today has the possibility to deliver plastics as well in a transparent bag when the paper is collected.

Vehicles Fredrikstad municipality today have 23 waste collection lorries, they have 8 one chamber vehicles on diesel, 4 two chamber vehicles on diesel and 11 one chamber vehicles on biogas. The two chamber vehicles cannot be on biogas as they will be very heavy which will decrease the allowed weight of waste they can carry.

To model the vehicles an Ecoinvent process of a similar waste lorry was used and adjusted for the numbers of our system. To account for the weight difference in the diesel, biogas and two chamber vehicles the biogas vehicle was multiplied by 1,2 and the two-chamber diesel vehicle by 1,1. In the future scenario it will be assumed that the amount of vehicles used for waste collection in Fredrikstad will remain the same. The amount of fuel used by the vehicles have been given by Fredrikstad.

Facilities A similar facility infrastructure was found from Ecoinvent and adjusting for the numbers of our system. The infrastructure of the already existing facilities, such as the incineration plant FREVAR and the biogas facility will be neglected. For the central sorting facility numbers from ROAF will give the expected power use under operation.

Waste flows Residual waste As already explained in the in depth system study, in Section 2.2.2 the residual waste composition will change from today to the new system. The composition today is given by a waste test performed by Mepex in 2021 (Syversen et al., 2022).

Replacements I will assume that the plastic types are replaced by 90% of recycled plastic of the respective plastic type, as nor all recycled plastics will be able to replace virgin plastics.

The food waste will in the biogas facility will be converted to biogas and fertilizer. The biogas is assumed to substitute diesel, that otherwise would have been used in many of the waste collection vehicles. The argument being that Fredrikstad could benefit of this by making more of their vehicle fleet drive on biogas. One ton of food waste is assumed to give 118 Nm3 biogas (Modahl et al., 2016) which with the assumption that 1 Nm3 biogas equals 1 litre of diesel (Miljødirektoratet, 2020) and that 1 tonne of diesel equals 1183 litres diesel (SEAI Statistics, 2019), the 1 tonne of food waste will substitute 997 kg of diesel. Furthermore, there will be produced a fertilizer, which will be assumed to substitute ammonium nitrate production and phosphorus fertiliser production. The nitrogen and phosphorus content of food waste is respectively 23 kg nitrogen per tonne dry matter and 3,8 kg phosphorus per tonne dry matter (Modahl et al., 2016). These will have to be multiplied with a dry matter content of 33,5% and subtracted a reject of 15%. Furthermore, the nitrogen is dried resulting in a loss of 75% of nitrogen, lastly only 60% of the nitrogen will be able to replace mineral fertilizer (Modahl et al., 2016). This leaves us with around 1 kg nitrogen and 1,1 kg phosphorus per tonne of food waste treated.

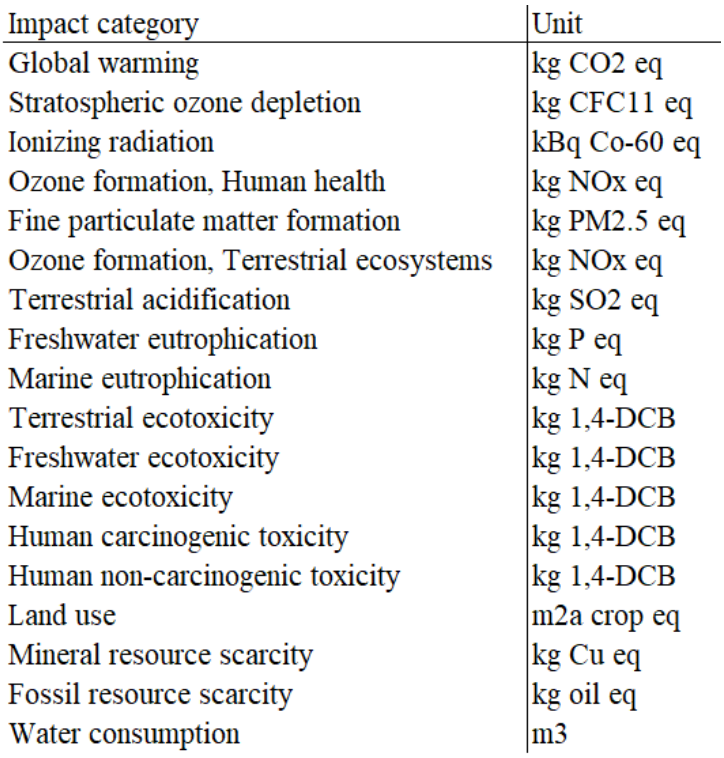
The residual waste burned will be assumed to replace natural gas.

There are not Norwegian numbers for all processes in Ecoinvent. When possible European or Swiss numbers will be used. The latter is a good approximation because Switzerland also have an electricity mix consisting of much renewable energy and in that way are quite similar to Norway.

2.3.4 Life cycle impact assessment

This section will describe the impact categories chosen in the study.

There are many impact categories that can be looked at. Such as global warming potential, land use, ecotoxicity and eutrophication. The most known might be carbon footprinting looking at the global warming potential, GWP, measured in carbon dioxide equivalents. Nevertheless, looking at solely one impact category gives a to narrow approach to give proper grounds for decision making concerning waste management solutions (Raadal et al., 2009). The following table shows all 18 impact categories that will be looked at in this study



Impact category	Unit
Global warming	kg CO2 eq
Stratospheric ozone depletion	kg CFC11 eq
Ionizing radiation	kBq Co-60 eq
Ozone formation, Human health	kg NOx eq
Fine particulate matter formation	kg PM2.5 eq
Ozone formation, Terrestrial ecosystems	kg NOx eq
Terrestrial acidification	kg SO2 eq
Freshwater eutrophication	kg P eq
Marine eutrophication	kg N eq
Terrestrial ecotoxicity	kg 1,4-DCB
Freshwater ecotoxicity	kg 1,4-DCB
Marine ecotoxicity	kg 1,4-DCB
Human carcinogenic toxicity	kg 1,4-DCB
Human non-carcinogenic toxicity	kg 1,4-DCB
Land use	m2a crop eq
Mineral resource scarcity	kg Cu eq
Fossil resource scarcity	kg oil eq
Water consumption	m3

Table 2: Impact categories

Assumptions for lower heating values, LHV, for the waste typeswere made from (Raadal et al., 2009; Schmidt, 2016; Areeprasert et al., 2017).

2.3.5 Database

To perform the LCA adn get background data Ecoinvent 3.8 will be used with allocation at point of substitution. Moreover ReCiPe Midpoint H is choosen.

3 Results and discussion

In this section the results of research question 1 and 2, described in Section 1.2 will be presented and discussed. Next, proposals for future work and recommendations will be presented.

3.1 Main findings in relation with research questions

3.1.1 RQ1

The first research question aimed at understanding how the waste flows will change. With the assumptions described in Section 2.2.2 we get a new waste composition of residual waste in the central sorting scenario that will enter the central sorting facility, shown in Figure 10.

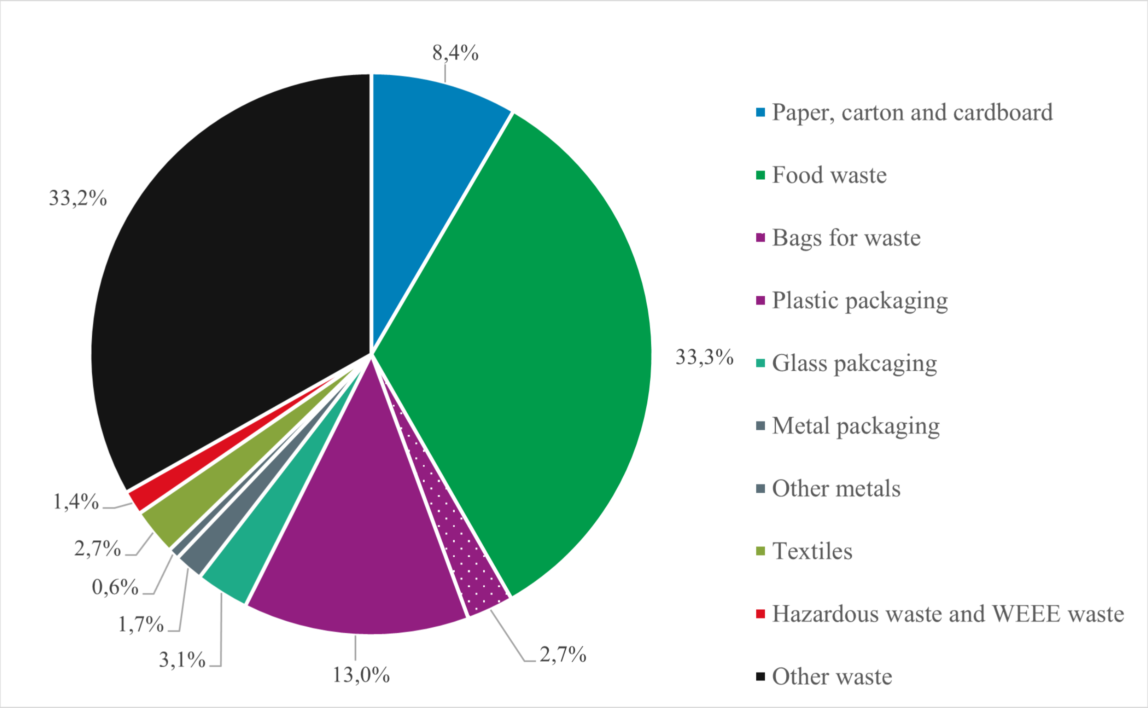


Figure 10: central sorting scenario of the composition of residual waste source separated at the households.

We see from the figure above that the residual waste will still contain 33,3% food waste after source separating of food waste, and consist of around 15,7% plastic waste in total where 13,0% is plastic packaging and 2,7% is plastic bags used to throw the waste. Since the decrease in food waste is bigger than the increased weight by plastics all the other waste types increase in the total percentage. The waste type "Other waste", with composition described closer in Section 2.2.2, being the biggest waste type in the manual sorting scenario increases the most, going from 25% to 32,7%, yet it is still the same amount of waste, just an increase in percentage.

With the composition in the manual scenario and in the central sorting scenario it can be created a flow diagram of how the flows will look. In the following figures the waste flows of the manual sorting scenario and the central sorting scenario is presented.

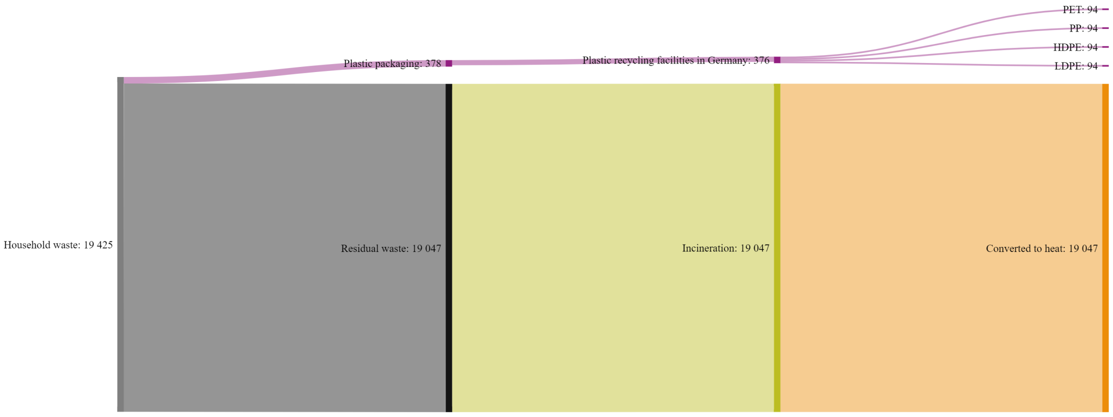


Figure 11: Waste flows of the waste management system today. Numbers in tonnes.

In Figure 11 it can be observed that the residual waste flow is large compared to the plastic packaging waste. The fact that the plastic is small is natural as plastics is a lightweight material and the figure is in tonnes. The plastic is sent to Germany, and the information about how the distribution of plastic types being sorted by them is not obtained, and thus they are drawn as equal in the figure.

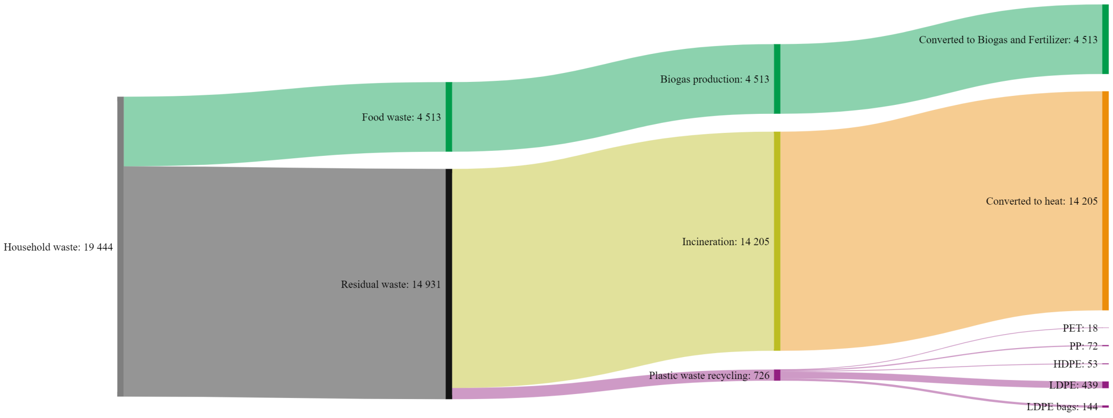


Figure 12: Waste flows of the waste management system in the future. Numbers in tonnes.

In the central sorting scenario we see that the amount of plastic packaging that goes to recycling is higher than in the manual sorting scenario. The plastic waste sorted increases from 378 to 726 which is almost a doubling of waste sent to recycling. Furthermore there is a big amount of food waste that is now going to biogas production rather than to incineration.

A difference in the plastic sorting is that in the manual sorting scenario, the amount of plastic sorted is depending on the inhabitants, while in the central sorting scenario the central sorting facility is what will limit the output of plastics. In the manual scenario there are several factors that could improve the sorting, such as enlightening the inhabitants on what plastic packaging is and why they should throw it in plastics instead of in residual waste. There is also an option to have economic incentives, such as free emptying of the recycling bins and higher prices on residual waste bins depending on the size or other pay as you throw schemes. Yet, in the end you are depending on the inhabitants to do the sorting correctly. In the central sorting scenario on the other hand, all plastic waste goes into residual waste and through the central sorting facility, an thus, how much is sorted out will depend on the facility itself. , for example how fast you run the facility can influence how well its able to sort. Furthermore a facility like this is driven by economic factors as well, and since incineration is one of the things that give income through selling heat, it could be more beneficial to burn the plastic rather than selling it, since plastics have a high calorific value. For example in the case where the price for heat is higher than selling the plastic for recycling. There has also been seen that the plastic packaging has to become easier to scan for the machines, and that for example some have used one type of plastic for the package and another for the logo, which makes the facility not sort it into the correct place.

Things we cannot see from this picture is the quality of the plastics. Today Fredrikstad delivers plastic packaging with only 3% pollution Grønt Punkt Norge (2022), and thus the output in the manual sorting scenario is good. The quality of the plastic in sorted from the central sorting facility could have higher amounts of pollution, as it has been mixed with all the other components of the residual waste, including food waste. The figures clearly shows that the central sorting scenario sorts more plastics, but whether this plastic is of a high quality for recycling is uncertain. Even though the plastics will not get sorted out if they have big contamination. How the central sorting facility performed also depends on technological boundaries.

For the food waste the amount being sorted is uncertain, as the inhabitants in Fredrikstad municipality might not behave the same as what was seen in the examples of ROAF, furthermore some inhabitants will continue using home compost while its a possibility some will continue throwing food in residual waste.

3.1.2 RQ2

Research question 2 was set up to answer what the environmental performance of altering the waste management system is. Performing an LCA to answer this was concluded to be expedient as described in Section 1.2 and the methodology is described in Section 2.3. Using the methodology the first result can be seen in Figure 13 which shows the total improvement in percent from the manual sorting scenario to the central sorting scenario for all impact categories. Improvement in this case means an reduction in impact, which is good.

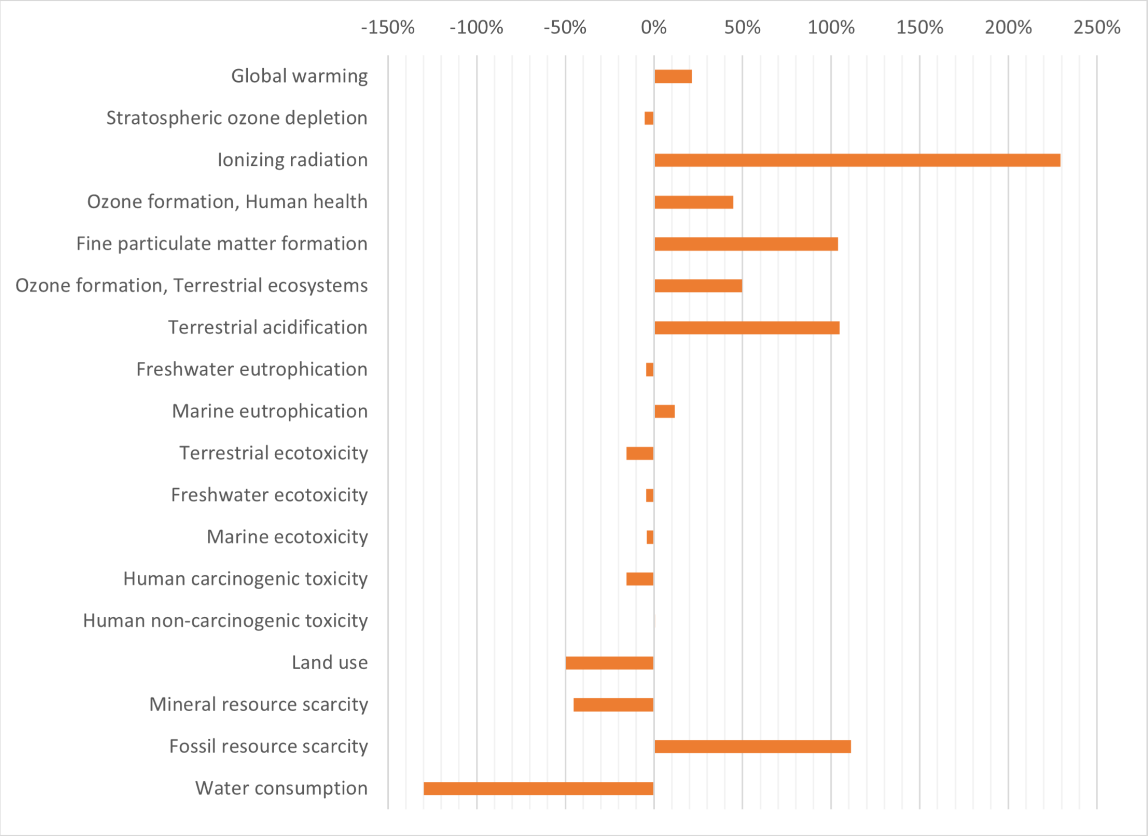


Figure 13: Result showing the difference in percentage from the manual sorting scenario to the central sorting scenario.

From the figure above one can read that the central sorting scenario has a lower impact in half of the impact categories compared to the manual sorting scenario. Note that the impact categories have different units as shown in Table 2 and therefore the figure does not show a comparison between the categories, solely the percentage improvement or decrease they have had compared to their respective values in the manual sorting scenario. To get a better understanding of which method is the best there is a need to look deeper into the different impact categories and how they are affected by the different processes of the waste management system.

The big picture from looking at the results is that the facilities have the largest impact, and compared to the facilities the impact of the waste bins, the vehicles and the fuel are quite small. This is so for the majority of impact categories. This can be illustrated by looking into global warming potential, GWP, first as the results for the GWP is important to Fredrikstad municipality, as they have stated in their climate plan that they want to reduce their green house gas emissions by 60% by 2030 (Fredrikstad kommune, 2019). In Figure 14 we see the impact the two scenarios has on the global warming potential for the total and for all of the life cycle steps of the assessment.

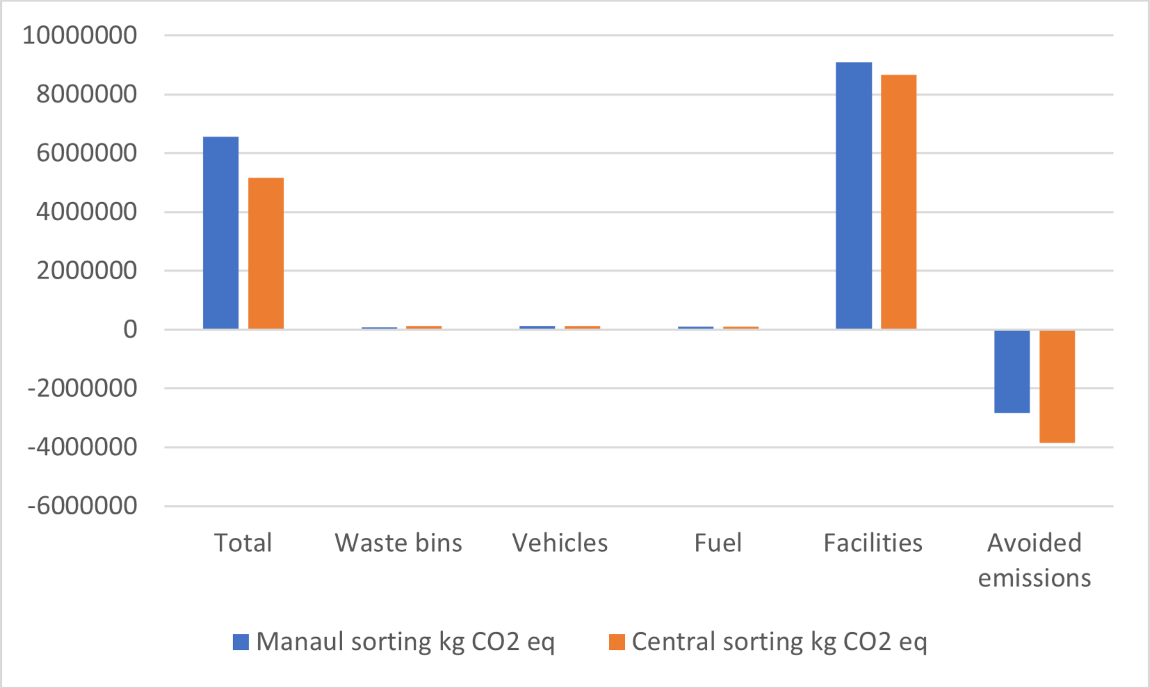


Figure 14: Result showing the Global warming potential of the manual sorting scenario vs the central sorting scenario

The facilities stands out clearly as the life cycle step with the highest impact for both scenarios with the manual sorting scenario emitting the most CO_2-equivalents. But they are not very different. The avoided emissions contributes to get a larger difference in the total emission between the two scenarios, as the avoided emissions are bigger for the central sorting scenario.

Compared to the emissions from the facilities and the avoided emissions it is clear from the figure that the waste bins, the vehicles and the fuel they use becomes of little significance. The waste bins have a slightly higher emission of CO_2-equivalents in the central sorting scenario which is caused by the introduction of food waste that needs waste bins, as explained in the methodology Section 2.2. The vehicles and the fuel have the same emission in both scenarios as was assumed in the methodology, and as can be seen from the figure even a doubling in waste bins, fuel consumption and vehicles would cause only a negligible increase in emissions, and therefore these assumptions can be expected to be accurate enough to not majorly affect the outcome of this analysis. The low impacts of these parts of the system could justify the acquiring of more equipment, such as waste bins and vehicles, to collect the food waste, or needing more driving to collect it, as the central sorting scenario still will be better. Yet, solely because the other categories are smaller compared to the facilities, does not mean they are insignificant.

Looking into the emissions from the facilities, in the manual scenario the biggest contribution towards climate change is the burning of residual waste. The plastic waste is what contributes the most, followed by the burning of “other waste”. In comparison to the burning of the residual waste the contribution from the facilities in Germany is small. In the central sorting scenario the same results can be observed; the burning of residual waste is the bigges contributor to emissions with plastic waste followed by the “other waste” contributing the most. The biogas facility contributes slightly more than the operation of the central sorting facility.

In the manual sorting scenario its also the avoided emissions from getting district heat produced from the burning of waste. The central sorting facility in Germany also contributes, but is smaller. In the central sorting scenario the biggest contributor to avoided emissions is the recycling of plastics, in other words avoiding production of virgin plastics. This is followed closely by the avoided emissons from burninig waste and producing heat.

Looking at the water consumption, because it has a surprisingly big percentual increase in wateruse for the central sorting scenario. The biggest impact comes from the electricity used in the central sorting facility, and not by the waste management processes in themselves. This is a Norwegian electricity process with a big part of hydropower, where the impact comes from from a process of water used in the turbines. The argumentation in the Ecoinvent process for this being water consumption is that while the water passes through the power plant and the turbines the water is taken from natural water balance for a while and in reservoirs. The amount of water passing through a hydro power plant can be big, but this number is not regionalized and hence, not taking into consideration that water is not scarce in Norway. This water is also turned back into nature, in contrast to processes where the water is used in the final product, which could be an argument to work with net values for water consumption in hydropower plants. According to a paper on water consumption of hydropower reservoirs in Norway the average net water consumption is 0,0016 m^3/kWh (Dorber et al., 2019), where the Ecoinvent process used in this analysis has a 0,8100 m^3/kWh for the turbines which is a substantial difference. For the purpose for this analysis the other facilities are not using local power because they use for example an incineration process that has not been defined for Norway. Here Switzerland has been used as described in Section 2.3 because of the similarities Switzerland and Norway has in energy mix. Here this can have contributed to a skewed result.

Taking a deeper look at the facilities as, for all impact categories, except land use, the facilities is the process with the highest impact. Looking into this the facilities score slightly better in the central sorting scenario in all impact categories, except for water consumption, as can be seen in Figure 15.

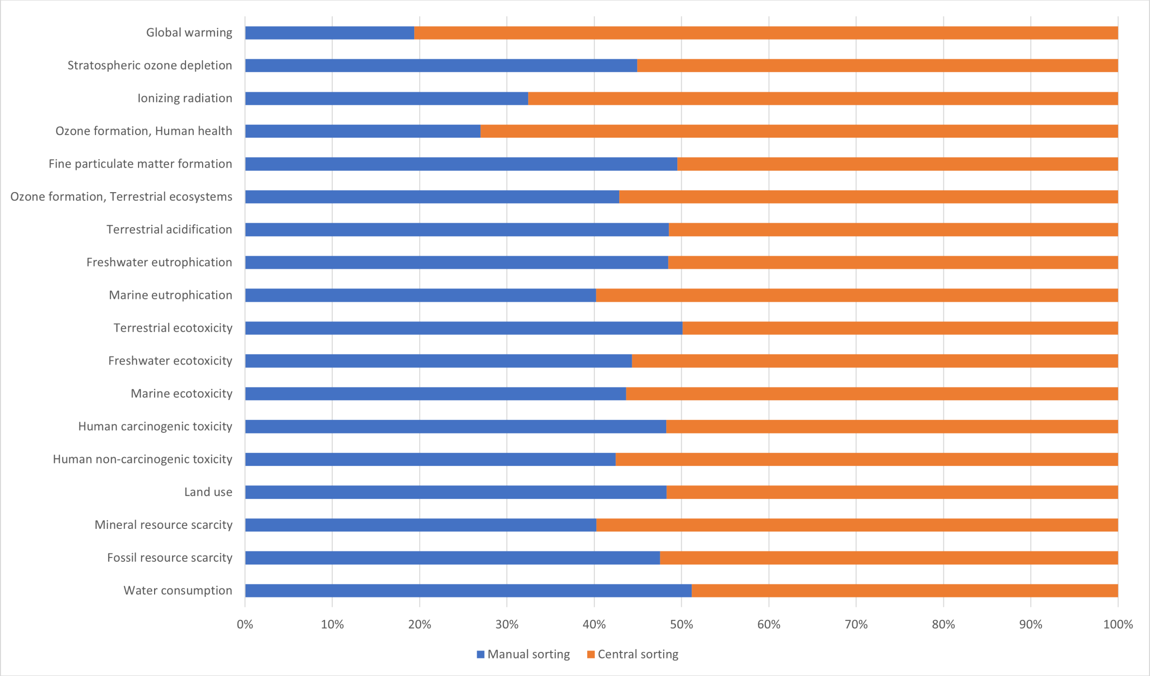


Figure 15: The total impact in all impact categories for the manual sorting scenario versus the central sorting scenario

The GWP, Ionizing radiation and ozone formation are the only ones that improve by more than 60% while the others are between 50 and 60%. For both scenarios the energy utilization from burning the waste contributes the most. In Figure 16 the contribution of the different waste types can be seen for the manual scenario and in Figure 17 for the central sorting scenario.

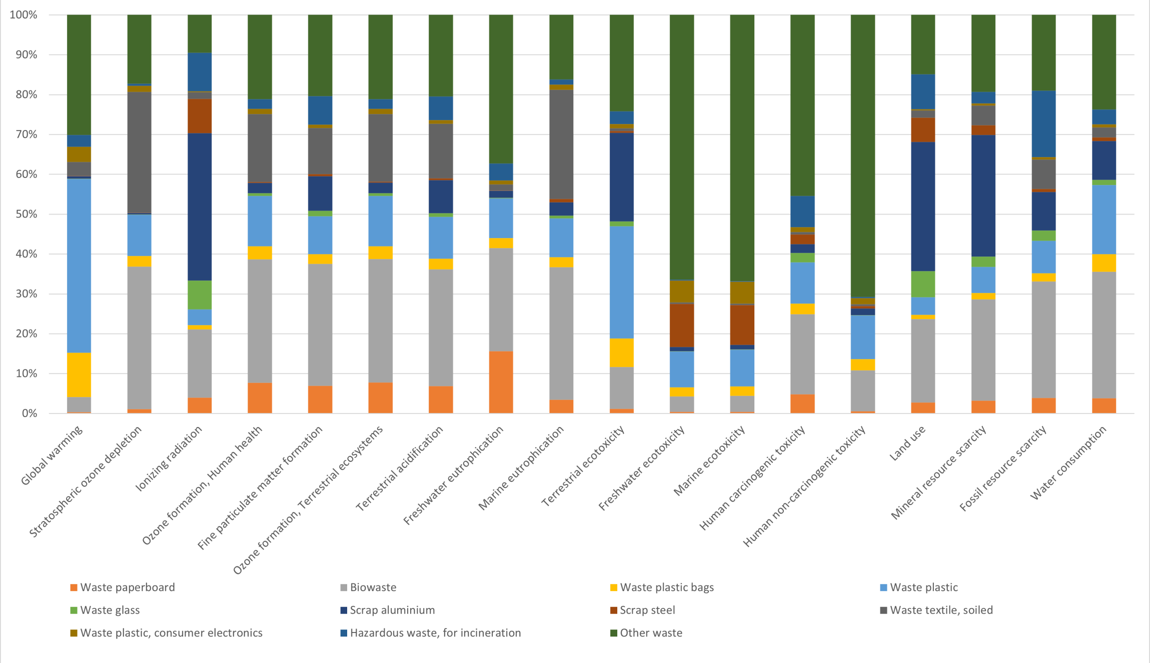


Figure 16: The total impact in all impact categories for the manual sorting scenario

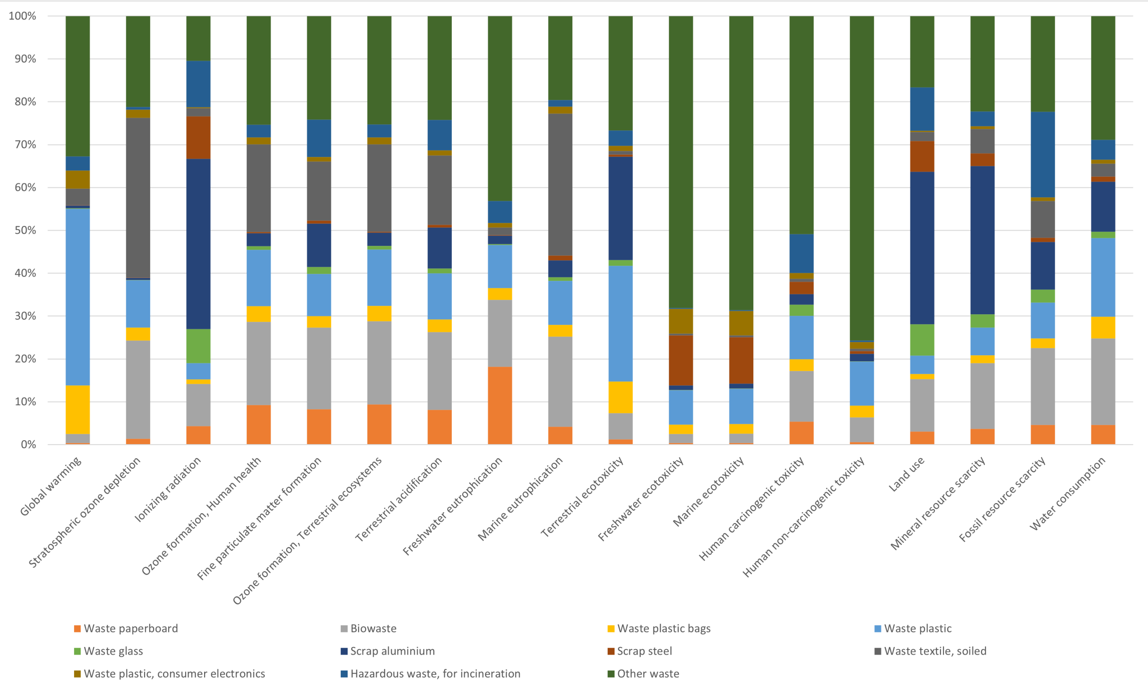


Figure 17: The total impact in all impact categories for the central sorting scenario

On can see that in most of the impact categories, the "Other waste" is one of the bigger reason for the impacts. As the composition of this waste is unknown, a lower heating value for municipal solid waste was chosen, this result shows that to know how much heat you get this value is important. However it should not affect this analysis as both scenarios has got the same assumption. This is also the only fraction that should have been in the residual waste, as all the other waste categories could have been recycled (Syversen et al., 2022). Textile has a quite high impact in some categories for example stratospheric ozone depletion and marine eutrophication. The latter seems a bit odd as most clothing don't contain phosphorus to be released when burned, and the Ecoinvent process do not write anything that helps in understanding where this comes from. Scrap aluminium also has a big impact in more categories, such as ionizing radiation, terrestrial ecotoxicity, land use and mineral resource depletion. The impact of this might be lower as the facility in FREVAR have machines to remove metals before the burning, but the figure clearly shows that for the mentioned categories is matters whether the aluminium has been sorted or not. The plastic waste and the plastic bags in respectively light blue and yellow in the figure also visibly contributes in all categories. Especially for GWP, as commented earlier. One can see that the impact from burning biogas has decreased, which is logical as the percentage of food waste has gone down due to the implementation of food waste sorting.

Over to discussing the avoided emissions have the biggest savings in the central sorting scenario for all impact categories. The biggest contributor to avoided emissions in the central sorting scenario is the avoided emissions from recycling plastics in all impact categories. In the manual scenario the avoided emissions from recycling in Germany is the biggest contributor for most impact categories, such as for all the toxicity categories, but for GWP, stratospheric ozone depletion and fossil resource scarcity the avoided emissions from incineration waste is the biggest. For the plastic the assumptions for the German facilities are from the Furberg et al. (2022)

while the assumptions for the central sorting scenario from the obtained information given by Fredrikstad municipality described in Section 2.3, this could create some differences in the results. The plastic type that contributes the most to the avoided emissions in central sorting scenario is LDPE, which is logical as this plastic type had the highest rate of sorting in the central sorting facility.. All in all, the plastic contributes the most, but the biogas also contributes. The biogas was assumed to substitute diesel and fertilizer and it is the avoided diesel that stands for the biggest avoided emissions. Burning of residual waste contributes for GWP and fossil resource scarcity, but is rather small for the other impact categories as can be seen in Figure 18.

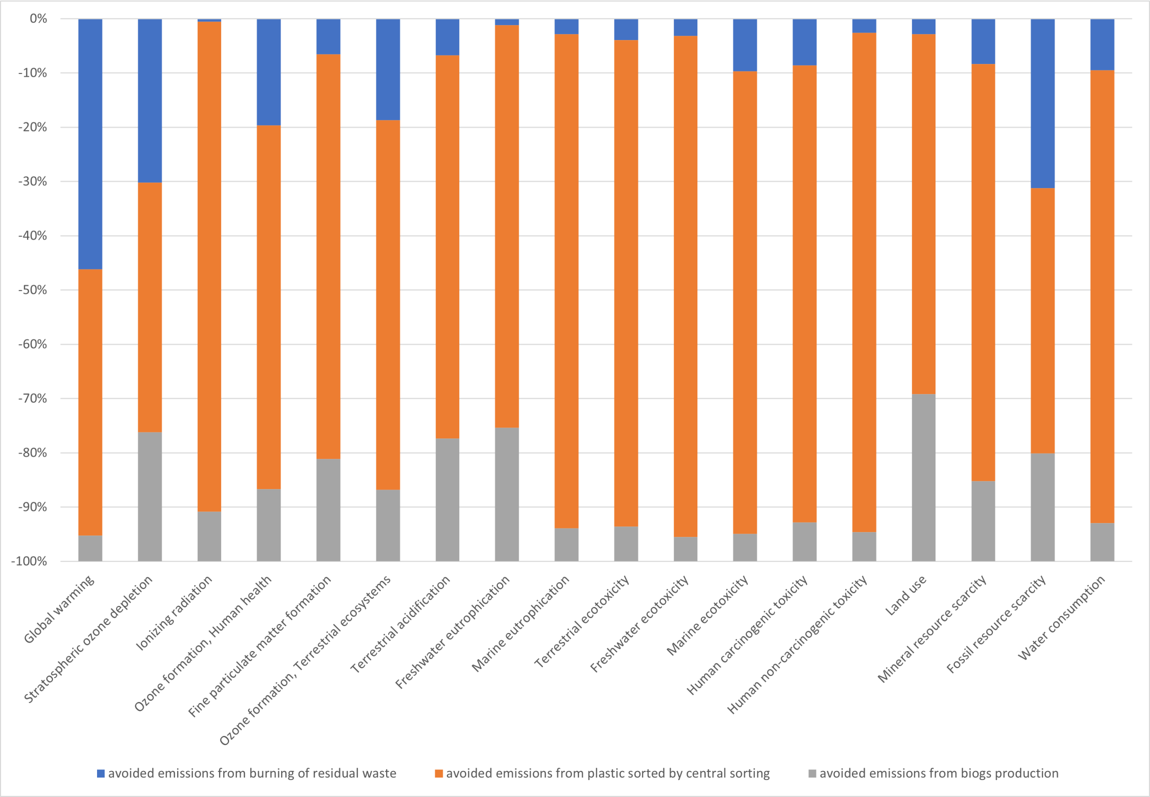


Figure 18: The total avoided emissions in all impact categories for the central sorting scenario

It is important to remember that the LCA is a comparative analysis. Additionally, the method is not perfect, and not all environmental impacts get captured by the method. For example work environment and the impact of microplastics lost in the process could be relevant for waste management. Yet they are difficult to quantify with an LCA due to lack of data or methodology (Hauschild and Barlaz, 2011a).

3.2 Further discussion

As seen in RQ1 the amounts of plastic waste is quite small in weight compared to the residual waste. But from the LCA we see clearly that the plastic fraction is important, for example the emissions from burning plastics contributes a lot to GWP and the avoided burden is high when replacing virgin plastics.

Looking at Figure 11 and Figure 12 one see that the amounts of plastic are small compared to the food waste, and in order to increase material recycling it could be tempting to focus solely on food waste. Nevertheless, the plastic waste is still important for the environmental impact, as the incineration of plastic is significant and the avoided emissions from recycling plastics were big in both scenarios. The LCA showed that the biggest emissions are caused by the facilities. Thus, an increased use of vehicles or fuel consumption, by needing to drive more, might be justified. Nevertheless, this might not hold in economic terms. The investment in such a facility is significant, and we see in the LCA results in Figure 13 that even though the impacts are mainly better in the central sorting scenario the improvements are not very big. Thus, the economic weight of such a project could be big compared to the environmental savings.

In the erspective of the circular economy another question is what matters the most. Reducing the consumption, or recycling more. For food waste we already know that the effect of cutting food waste is much bigger than the avoided emissions of biogas, and there is reason to believe it is the same for other products of waste.

There is always uncertainty connected to avoided emissions. And the choices are of importance for how big the avoided emissions will be. For example, plastic waste can be flaked and used directly to make a new product, another method is to make granulate which in turn will be moulded into a new product. But the granulation will have more losses in the process. Another question is if there is a market for the plastics. The plastic could be of too poor quality to be recycled, or be of low value on the marked, connected to pollution, colors etc. In this task the sorting rates from the ROAF facility suggests that the pollution is not to high in these plastics Yet there is a qustion of why the other plastic was not recognized or approved by the machine, was it pollution, or maybe plastic mixed or packaging not designed for recycling.

The avoided emissions of biogs can also have uncertainties in regards to what type of fertilizer is being replaced and whether the farmers use this fertilizer instead of other or as an adittion to what they already use.

3.3 Future work

There are also private companies in Fredrikstad, like restaurants that has significant amounts of food waste. They choose who they want to collect their waste, and can choose sending their food waste to FREVAR or other waste companies. If they use FREVAR this would contribute to the amounts of biogas produced, the size of this contribution could be looked upon. Collecting data on this topic is relevant future work.

The Life cycle assessment does not cover whether the quality of the plastic of the two systems are comparable. As mentioned, Fredrikstad municipality per date delivers plastic with very little pollution, if this worsens in the central sorting facility is not known. Nor is it certain if there is a market and how much virgin plastics the recycled plastic will replace. Not being able to assess the quality of the plastics is a limitation of the LCA methodology.

How clean the plastic is when it enters thecentral sorting facility also affects how much gets sorted out as the facility will not sort out highly polluted plastic. So, to get the best quality plastic out of the central sorting facility it is crucial that the food waste gets sorted out separately, as it can pollute the plastic if they are thrown together, and here will still be foodwaste in this fraction after the implementation (Bjørnerud and Hultin, 2021). From this we can conclude that the consumer behavior and willingness to sort food waste properly is important. It is also worth noticing that the plastic needs to be clean when thrown, both in the system today and in the new system. For the case of Fredrikstad we have seen that the plastic fraction is clean and of high quality (Grønt Punkt Norge, 2022), but will this still be the case when inhabitants are throwing the plastics in the residual waste? This is interesting future work in this topic.

LCA is one way of comparing, a future analysis could have looks at the introduction of the facilities in e.g. be in monetary terms.

In order to use the results of this analysis for deciding whether or not to implement a central sorting facility the impact categories would benefit from weighting their importance in relation to each other in the waste management field. The case study Fredrikstad had prioritized Global warming potential, although the relative importance of the others is more uncertain and determining this is relevant future work for the case study.

4 Conclusion

The following section summarizes the study and draws it's main conclusions.

When introducing sorting of food waste and the central sorting facility to the system the waste flows change. Using principles from Material flow assessment (MFA) two main results were seen. Firstly, the amount of food waste in the residual waste goes down as the inhabitants source separate food waste at home, secondly the central sorting facility gives an increase in sorted plastic waste as it sorts out more plastic than the inhabitants of Fredrikstad manages today. The sorting facility almost doubles the amount of plastic sent to recycling. This shows that implementing a central sorting facility is beneficial for increasing the recycling rates for plastic packaging and food waste.

The impact categories looked at in the Life cycle assessment (LCA) gave split results of which scenarios had the lowest impact on the environment. However the central sorting facility has the greatest improvement on the system if all factors are of equal importance. Half of the factors are affected positively and half of the factors are affected negatively, as such it is necessary to determine the importance of the factors relative to each other in order to effectively compare the systems. Although one of the main negatively impacted factors, the water consumption, can be of less importance than shown, in the specific country of this study due to the fact that in Norway water is not considered scarce, which improves the ratio of positive impacts further of implementing the central sorting facility. As discussed Fredrikstad municipality prioritises improvement in the Global Warming Potential (GWP) in their Climate strategy. The results show that GWP is performing better in the central sorting scenario, and as such these results implicate that the implementation of a central sorting facility is beneficial for their main concerning impact, and possibly according to the full set of impact categories as well. The future work section details the need for weighting the impact categories in relation to each other.

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