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# Analysing the sustainability performance and critical improvement factors of urban municipal waste systems - case study RfD

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# MASTER THESIS

for

Student Nora Omdal Schjoldager

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Analysing the sustainability performance and critical improvement factors of urban municipal waste systems – case study RfD

*Analyse av bærekraft og viktige faktorer for forbedring i byers avfallshåndtering – Casestudie RfD*

## Background and objective

As a result of continued economic growth, higher purchasing power and lower life cycles of products, waste generation in Norway has increased the last 10 years, and currently it is at a level of some 477 kg per capita.

Waste generation is wasted resources and additional resources consumed in its management. Fortunately, when well managed, a majority of waste flows can be refined and reclaimed into useful material and energy flows for society, with a potential to replace virgin material extraction and its corresponding climate emissions as well as other environmental impacts. Known as the circular economy, it aspires to keep products and materials within the economic system instead of moving them into the final sink of land disposal.

At present, there is a lack of knowledge concerning what determines the environmental and economic efficiency of material and energy recovery in waste systems, from a systems perspective for different kinds of waste flows. To measure and explore what factors and variables that influence this efficiency, or more specifically, the performance of given value chains within a waste system with regards to energy, materials and emissions, one needs an appropriate system definition and the use of a systems quantitative model with appropriate performance indicators.

The objective of this master thesis is to model and analyse the system efficiency of the urban waste management system of RfD (Renovasjonsselskapet for Drammensregionen IKS) outside Oslo. The analysis shall take advantage of industrial ecology methods, such as material flow analysis (MFA), energy analysis (EA) and life cycle assessment (LCA), in order to identify critical system variables and factors for system performance, with a focus to energy use, energy efficiency, greenhouse gas emissions and costs. The starting point of the analysis shall be a model representation of the system in 2015, and a set of defined solutions in order to try to comply with targets for future increased material recovery from waste towards 2030.

The work will be carried out in collaboration with RfD, with Ellen Svendsvoll as contact person, and is a continuation of a project work carried out during the fall of 2016.

**The following tasks are to be considered:**

1. Carry out a literature study on topics of relevance to this project, with a focus on energy use, energy efficiency and GHG emissions in urban waste systems.
2. Collect the information needed to describe the recent and current management situation of selected waste categories for the case study, as well as possible new solutions in line with RfD's plans for how to comply with (circular economy motivated) targets for future material recovery towards 2030. Collect the data needed to model and analyse the system performance with respect to energy use, energy efficiency, GHG emissions and costs for these situations, including data from RfD and other relevant sources.
3. Develop an MFA-based model with an appropriate system boundary and resolution of processes for the given urban household waste flows, including a mass flow layer and an energy layer. Use LCA-methods to support the estimation of GHG emissions, and LCC-methods to support the estimation of costs. Define the criteria and indicators appropriate to determine the system and possible sub-system efficiencies for materials, energy and emissions.
4. Use the model(s), with its/their constituent processes and flows, to analyse the current situation and selected scenarios for future management of the given waste flows towards 2030. Assess and compare the system performance for each scenario, and examine critical system variables and factors that highly influence relevant performance levels.
5. Discuss the main findings of your work; i.e. levels of performance for different waste categories, influencing variables and factors, the effect of possible new solutions, and agreement with literature. Discuss the strengths and weaknesses of your work and the methods you applied. Finally, suggest recommendations for future work.

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analysed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

Pursuant to “Regulations concerning the supplementary provisions to the technology study program/Master of Science” at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student’s name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 15. January 2017

Professor Helge Brattebø
Academic Supervisor

Co-supervisor: Associate professor Sigrun Jahren

# Preface

This master's thesis is written as a part of a master's degree in Energy and Environmental Engineering at The Norwegian University of Science and Technology (NTNU). The work has taken course over the spring semester 2017. The author specializes in Energy Systems Planning and Environmental Analysis.

The objective of this project is to model and analyse the system efficiency of the urban waste management system of RfD. In agreement with the supervisor, has the model in the project work been limited to a mass flow layer, an energy layer and an emission layer. A cost layer will not be included.

The author would like to thank her academic supervisors Helge Brattebø and Sigrun Jahren for guidance, inspiring discussions, and constructive criticism. Second, I would like to thank my classmates Pieter Callewaert and Silje Madalena Oliveira Unander for all their help, especially Pieter who has developed the model and has been invaluable in the process of adapting the model to my system. I also want to thank RfD, especially Ellen Svendsvoll and Gry Nessjøen, for providing data, availability and support. Lastly, I would also like to thank Olav Skogesal in Mepex Consult AS.

Trondheim, 5. July 2017

# Summary

The objective of this master's thesis is to analyse the environmental performance and critical improvement factors of urban waste systems. The thesis is a case study of the urban waste management system of RfD (Renovasjonsselskapet for Drammensregionen IKS) nad has been carried out in collaboration with them. RfD collects the municipal solid waste from the households in the Drammen region.

A literature study examines the relevant theoretical background regarding the waste management system, environmental performance and introduces relevant performance criteria. Based on these fundamental clarifications and findings, the used model to analyse the current situation and predicting future scenarios is then introduced before the actual case study is conducted.

The model is adjusted and applied on the given data of RfD's urban waste management system for the year of 2015. To analyse the current situation and compare them to future development, the years of 2015, 2025 and 2030 have been modelled. The model focuses on mass flows, energy use and CO2 emissions connected to relevant processes in the system. Different scenarios are examined in each year, the *reference scenario* represents "business as usual". For 2025 and 2030 the following scenarios are investigated: the *more underground* scenario, where a larger share of the collection containers are underground, and the *biogas* scenario, where parts of the collection vehicles are fuelled by biogas. For the year of 2030 a scenario called the *central sorting* scenario is also modelled, which includes a central sorting facility in the system.

The results of the analysis showed that material recycling, energy efficiency and GHG emissions are closely connected. Increased material recycling leads to a lower energy efficiency, but also lower GHG emissions and thus a better environmental performance. Increased material recycling can be achieved through improved sorting. Plastic and organic waste have here been identified as critical factors for the environmental performance of the system. Incineration has resulted to be the largest contributor to GHG emissions and should therefore be targeted. The system's GHG emissions are highly dependant on the energy consumption of the system as well as chosen CO2 emission factors.

Based on the results of this work, recommended measures for RfD are implementing a central sorting facility and encouraging better sorting in the households. The transition to collection vehicles fuelled by biogas proved to have a positive impact on the environmental performance of the waste management system.

# Sammendrag

Målet med denne masteroppgaven er å analysere bærekraften og viktige faktorer for forbedring i byers avfallshåndtering. RfD (Renovasjonsselskapet for Drammensregionen IKS) er brukt som case. RfD er ansvarlig for innsamling av husholdningsavfall i Drammensregionen. Masteroppgaven er skrevet i samarbeid med RfD.

En litteraturstudie undersøker relevant teoretisk bakgrunn, bærekraften i avfallshåndtering og introduserer relevante prestasjonskriterier. En modell basert på disse fundamentale funnene, er brukt til å analysere det nåværende systemet. Modellen og aktuelle fremtidige scenarier presenteres før casestudiet utføres. Caset defineres ved relevante fakta om RfD. Systemgrenser, relevante prosesser, strømmer og avfallsfraksjoner som skal modelleres og analyseres spesifiseres.

Modellen er tilpasset og tatt i bruk for de oppgitte dataene for RFDs avfallshåndteringssystem i 2015. For å analysere den nåværende situasjonen og sammenligne den med fremtidig utvikling, er årene 2015, 2025 og 2030 modellert. Modellen fokuserer på materialstrømmer, energibruk og CO2utslipp knyttet til relevante prosesser i systemet. Ulike scenarier er undersøkt for hvert år, referansescenariet *the reference scenario*, representerer ”business as usual” hvor de eneste endringene skyldes en befolkningsøkning og en økning i generert avfallsmengde i regionen. Disse endringene benyttes i alle scenariene. I årene 2025 og 2030 er følgende scenarier undersøkt: *the more underground scenario*, hvor en større andel av innsamlingsbeholderne er nedgravd, og *the biogas scenario*, hvor en andel av innsamlingskjøretøyene benytter biogass som brensel. For år 2030 er også et scenario kalt *the central sorting scenario* modellert. Dette scenariet undersøker effekten av å inkludere et sentralsorteringsanlegg i systemet.

Resultatene av analysen viste at materialgjenvinning, energieffektivitet og drivhusgassutslipp er nært forbundet. Økt materialgjenvinning fører til lavere energieffektivitet, men også lavere utslipp av drivhusgasser og dermed en bedre miljømessig systemprestasjon. Økt materialgenvinning kan oppnås ved forbedret sortering. Plast og organisk avfall viste seg å være kritiske faktorer for systemets miljøprestasjon. Ettersom forbrenning er den største bidragsyteren til drivhusgassutslipp, bør denne prosessen være gjenstand for forbedring. Systemets drivhusgassutslipp er svært avhengige av systemets energiforbruk og valgte CO2-utslippsfaktorer.

Anbefalte tiltak for RfD er å implementere et sentralsorteringsanlegg og å oppmuntre til bedre sortering i husholdningene. Overgangen til innsamlingskjøretøy drevet av biogas viste seg å ha en positiv innvirkning på systemets miljømessige prestasjon.

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# Abbreviations

BAT - Bottom Ash Treatment

CO2 - Carbon dioxide

CO2-e. - Carbon dioxide equivalents

CH4 - Methane

EA - Energy Analysis

EC - The European Commission

EEA - The European Economic Area

EFTA - The European Free Trade Association

EU - The European Union

FA - Farlig avfall - Hazardous waste

GHG - Greenhouse gases

G&M - Glass and metal

GWP - Global Warming Potential

H2O - Water

ISO - International Standards Organization

kWh - kilowatt-hours

LCA - Life Cycle Assessment

LCI - Life Cycle Inventory

LCIA - Life Cycle Impact Assessment

LHV - Lower heating value

MFA - Material Flow Analysis

MSW - Municipal Solid Waste

NIR - Near InfraRed Radiation

N2O - Nitrous oxide

Org. - Organic waste

P&C - Paper and Cardboard

Plast. - Plastic waste/plastic packaging

Rest. - Residual waste

RfD - Renovasjonsselskapet for Drammensregionen IKS

RiG - Renovasjon i Grenland IKS

RoAF - Romerike Avfallsforedling

SSB - Statistisk sentralbyrå (Statistics Norway)

TC - Transfer Coefficient

TRV - Trondheim Renholdsverk AS

VESAR - Vestfold Avfall og Ressurs AS

WEEE - Waste Electrical and Electronic Equipment

# Chapter 1

# Introduction

This thesis is written as a part of a master's degree in Energy and Environmental Engineering at The Norwegian University of Science and Technology (NTNU). The project work has taken course over the spring semester 2017. The author specializes in Energy Systems Planning and Environmental Analysis.

The objective of this thesis is to analyse the sustainability performance and critical improvement factors of urban waste systems. This has produced the following research questions:

*1. How do measures motivated by circular economy influence the material recycling rate of the different materials in the system?*

*2. How do the measures for increased material recycling affect the energy consumption and GHG emissions of the system?*

*3. What are the critical factors of the system in terms of environmental performance?*

The thesis is a case study of the urban waste management system of RfD and the work has been carried out in collaboration with this company.

In Norway and the European Union, the waste management approach is based on the waste hierarchy, which defines the order of priority for different waste management measures. Waste prevention and minimisation has the highest priority, followed by reuse, recycling of materials, and recovery of materials and energy. Final disposal, including landfilling and incineration without energy recovery, has the lowest prioritisation. In the EU's transition towards a circular economy, the measures of material recycling and recovery of materials and energy have gained importance. The EU, and Norway, has presented ambitious targets for the waste sector towards 2030. To reach these targets, the waste sector will have to improve the performance in many of the processes that constitute the waste management system. Other important motivational aspects are environmental concerns like climate change and GHG emissions, energy use and decreasing natural resources.

It has been carried out a literature study to present a relevant theoretical background for the analysis. Waste policies and legislation, trends, relevant strategies and technologies as well as waste management performance criteria, are presented in chapter 2. Chapter 3 presents the applied methodology. The industrial ecology methods of material flow analysis and life cycle assessment are shortly presented in the same chapter. In chapter 4, the analysed system is thoroughly presented. In the following chapter the main results of the modelling are presented. A discussion of the results and the work in general is presented in chapter 6. The conclusion of the thesis can be found in the very last chapter, chapter 7. Additional information regarding the model, data and results can be found in the appendix.

The urban waste management system has been modelled using the method of material flow analysis, energy analysis and LCA. The model is made in the Microsoft Excel software and the calculations are done in the Matlab software, which is a software optimized for solving engineering and scientific problems. The language is matrix-based and is especially useful in computational mathematics. The model was developed by Pieter Callewaert in the summer of 2016 and modified in the spring of 2017. The model is based on the urban waste management system of RfD in the year of 2015. The years of 2015, 2025 and 2030 have been modelled to show the development in the system. Different scenarios are presented in each year, but a *Reference scenario* and a *Perfect sorting* scenario is analysed for all the years. In addition to this, a *More underground* scenario and a *Biogas* scenario, have been modelled for the years of 2025 and 2030. In 2030 a scenario with a central sorting facility is also investigated as well as a scenario, *All scenarios*, that includes the changes from the *More underground* scenario, the *Biogas* scenario and the *Central sorting* scenario. The *reference scenario* in 2015 is based on the actual data for the year of 2015, as far as possible. Assumptions have been made if necessary where required data has not been available. The reference scenario in 2025 and 2030 follows business as usual, the only changes are caused by a growth in population and the amount of generated waste in the region. The same growth in population and waste amounts is assumed in all scenarios.

In agreement with the supervisors, the cost layer will not be a part of the thesis.

# Chapter 2

# Literature Review

## 2.1 Waste Management Policies and Legislation

The EC defines waste as "any substance or object which the holder disposes of or is required to dispose of pursuant to the provisions of national law in force." The term disposal includes collection, sorting, transport, treatment and the transformation operations necessary for its reuse, recovery and recycling. [Eurostat, 2014d] Municipal waste is defined as "waste collected by or on behalf of municipal authorities and disposed of through waste management systems." [Eurostat, 2013c] It is important to note that the definition of municipal waste in Norwegian legislation, "husholdningsavfall", does not include any kind of commercial or public waste, only the waste collected from households. [Lovdata, 2016] The EC definition includes similar waste from sources as commerce, offices, public institutions and selected municipal services, as well as bulky waste. [Eurostat, nd]

Like in many other countries in the Western World, the Norwegian waste management approach is based on the waste hierarchy. The waste hierarchy defines the order of priority for different waste management measures: 1. Waste prevention and minimization, 2. Reuse, 3. Recycling of materials, 4. Recovery of materials and energy, and 5. Disposal, including landfilling and incineration without energy recovery. The municipal waste management system consists of four different phases: 1. Generation, 2. Storage, collection and transport, 3. Treatment and 4. Products. [Brattebø, 2016b]

### 2.1.1 Circular Economy

The motivation behind this project is closely connected to the transition to circular economy and the new waste targets set by the European Union. The concept of circular economy is therefore shortly explained.

On page 55 in the book "Industrial ecology and sustainable engineering", Graedel and Allenby define metabolism as "the aggregate of all physical and chemical processes taking place within an organism or group of organisms" [Graedel, 2015]. In short, metabolism is the processing of energy and materials. It is the processes involved in utilising resources to perform a function. The organism can be biological or industrial, and in the latter case, we speak of social or industrial metabolism. This concept can be helpful in a transformation to a society with closed material loops, a circular economy. Ehrenfeld and Bohne argue that the whole economic system should be seen as a metabolic system that is a part of the surrounding ecosystem, exactly what industrial metabolism is about [Ehrenfeld, 2015]. When focusing on smaller processes, it is easy to forget that humans need and affect the physical system on the planet. Human societies should aspire to copy the closed loops in biological ecosystems, where nothing is turned into waste. Everything is used again. Ayres argues that a big part of the problem with the industrial society is that many of the products and materials are only used once, then they become waste.[Ayres, 1989] These days, and especially after COP21 in Paris in 2015, there is an increasing focus on circular economy and material recycling. The EU has set new targets for the amounts of waste that should be recycled and materials that should be recovered. The industrial society has based a lot of it's production on limited resources, not only fossil fuels, but also metals and other materials.

Urban mining is an important part of closing the loop in the economy. This concept is very important for waste management and material recycling and is based on the fact that materials are used where people are located, mostly in cities. The increasing urbanisation leads to an increase in in-use material stocks in cities all over the world. The natural stocks of many materials are shrinking, although it is difficult to predict when the exhaustion of virgin geological resources will occur. This means that materials will have to be recycled from the urban stocks, the urban mines. The in-use stocks are discarded by the owner when it no longer has any utility, but the length of service is highly dependant on the product. This means that there is a time delay in the system, as it is for waste in general. This time delay must be taken into consideration when the amount of available material is to be quantified. Graedel and Allenby argue that urban mining has several benefits for society, like saving energy and water, avoiding environmental impacts of mining and by mitigating problems of resource depletion by providing an alternative source of material. They state that an efficient system for collection and sorting of waste is an important requirement, among other, for the implementation of urban mining. [Graedel, 2015]

The concept of industrial metabolism applied to an entire economy is by many described as circular economy. The motivation behind implementing circular economy is mainly sustainability and environmental protection for most developed countries. For developing countries, like China, the motivation is often economic development. In 2002, the National Congress in China framed a goal for circular economy, but it is still too early to tell if the circular economy model will work in China, as both the circular economy concept and the implementation are in their infancy [Graedel, 2015]. The European Commission recently adopted a "Circular Economy Package" to stimulate Europe's transition to a circular economy. The package consists of an action plan and it includes legislative proposals on waste [EC, 2015a].

### 2.1.2 Legislative Targets

In the EC legislation there are certain terms that are key to the performance targets. Eurostat defines recycling of waste as “any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material, but does not include energy recovery”. [Eurostat, 2014b] Reuse of waste is defined as “any operation by which products or components that are not waste are used again for the same purpose for which they were conceived.”[Eurostat, 2014c] Lastly Eurostat defines recovery of waste as “any operation the principal results of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfill a particular function, or waste being prepared to fulfill that function, in the plant or in the wider economy.” [Eurostat, 2014a] Recovery includes recycling.

Some of the proposed targets for the waste sector are as follows:

- Preparing for reuse or recycling minimum 60% (by weight) of municipal waste by 2025, a common EU target.
- Preparing for reuse or recycling minimum 70% (by weight) of municipal waste by 2030, a common EU target.
- Recycling 75% of packaging waste by 2030, a common EU target.
- A binding target to reduce landfill to maximum of 10% of municipal waste by 2030.

[EC, 2015b] [Fund, 2017]

Through EEA will these targets, if adopted in the EU legislation, be adopted in Norwegian legislation. As of now are only the targets for 2020 adopted in Norwegian legislation. The binding target for 2020 is to recycle 50% of the municipal waste. Norway banned landfilling of biodegradeable waste in 2009 [Miljødirektoratet, 2014].

For packaging waste there are further targets specified in the directive on packaging and packaging waste. Table 2.1 shows the targets of the EC waste policy and legislation. [EC, 2015c] A new proposal of March 2017 raises the targets even further. [Martinussen, 2017] The 2008 targets were binding for Norway, but none of the targets for 2025 and 2030 have been adopted in Norwegian legislation. It is important to note that these targets applies to the total of all kinds of packaging waste, not just waste from households. [KLD, 2017]

There are no such targets for organic waste, but the Committee on the Environment, Public Health and Food Safety of the European Parliament has written a draft report on a “motion for a European Parliament Resolution on initiative on resource efficiency: reducing food waste, improving food safety” in which it is called for a binding food waste reduction target of 50% by 2030 and at least 30% by 2025, with 2014 as a baseline. These reductions are measured in reduction of food waste per capita. This draft report also urges the European Commission to swiftly adopt a common methodology to measure

**Table 2.1:** The EC targets for recycling of packaging waste and the new proposed targets.

| Waste type | 2008 | 2025 | 2030 | 2025 (new) | 2030 (new) |
|---|---|---|---|---|---|
| Plastic | 22,5% | 55% | Review | 60% | 60% |
| Metals | 50% | 75% | 85% | 80% | 90% |
| Glass | 60% | 75% | 85% | 80% | 90% |
| Paper and cardboard | 60% | 75% | 85% | 90% | 90% |

food waste. [Borzan, 2016] The targets for food waste reduction as well as other aspects regarding bio-waste were adopted by the European Parliament in the Plenary on March 14th in 2017. Other important aspects are obligatory separate collection of the main waste streams: paper, metal, plastic, glass and now also food waste. The more general target of 70% recycling of municipal waste with a 5% of that waste to be prepared for reuse by 2030 now also includes bio-waste.[Fund, 2017] In Norway, a proposal for a white paper by the Ministry of Climate and Environment, states that the government will investigate a requirement of sorting and material recycling of selected types of plastics and wet organic waste from households and parts of industry. This white paper was approved in government council the same day, 21st of June 2017. [KLD, 2017]

In Norway, it is the municipalities that are responsible for ensuring the collection of household waste and that there are waste facilities that can receive and treat this waste in an environmentally sound manner. Apart from the waste types hazardous waste and WEEE, that have specific regulatory requirements in the waste regulations, each municipality can decide which fractions that are sorted out and how the collection is done. [Miljødirekotoratet, 2017]

RfD's targets for the year of 2017, presented in "Selskapsstrategi for RfD 2014-2017", are among others, that the overall activity of the company shall contribute to a net climate gain of 100 000 tonnes of reduced CO2 emissions (1145 kg CO2 per household). Another goal is that a maximum of 30% of the waste becomes residual waste after sorting. [RfD, 2013]

## 2.2 The Present Situation and Future Trends

### 2.2.1 Trends in the EU

Eurostat collects and publishes data on municipal waste in the EU from 1995 to 2015. According to this data, municipal waste accounts for about 10% of the total waste generated, but it has a very high political profile because of its composition, character and its link to consumption patterns. The data on municipal waste is expressed in kilograms per capita and shows that for 16 of the 31 countries, the generation per capita increased between 1995 and 2015. The highest average annual growth rate was 2,5% and the highest decrease was -2,5%. For 2015 the waste generation ranges from 789 kg per capita in Denmark to 286 kg per capita in Poland. However, Eurostat states that these variations depend on how the municipal waste is collected and managed in the different countries, as there are no common regulations on this. [Eurostat, 2017]

When it comes to waste treatment methods, Eurostat separates between the methods of landfilling, incineration, recycling and composting. It is however not successfully separated between incineration with and without energy recovery. The most distinctive trend is towards less landfilling and more of the other treatment methods. The annual decrease in landfilling was of 4,0% and the annual increase in both recycling and composting was of 5,4%. [Eurostat, 2017]

### 2.2.2 Trends in Norway

According to SSB, the amount of household waste generated in kg per capita increased with only 5% from 2009 to 2015. And there was no increase from 2014 to 2015. The total amount of household waste increased with 12% from 2009 to 2015 and 1% from 2014 to 2015. The total amount of waste generated, on the other hand, increased by 7% from 2013 to 2014, mostly because of an increase in waste from the building sector. Household waste accounts for about 20% of the total waste generated in the country. When compared to Europe, household waste and commercial waste together make up municipal waste, Norway generated 423 kg waste per capita, which is around 50 kg less than the European average, according to SSB. This is however, as mentioned in the previous section, uncertain because of different ways of calculating municipal waste. [SSB, 2016b] [SSB, 2016a]

Norway has a few specific environmental national targets. One of them is that the growth in the quantity of waste generated shall be considerably lower than the rate of economic growth, expressed as change in GDP, and that the resources in the waste will be used through recycling and energy recovery. As of May 2016 is the growth in total amounts of waste from 1995 to 2014 about 60% and in the same the growth in GDP was less than 50%. For household waste the growth has been 1,1% between 2014 and 2015, while the private consumption of the households increased by 2%. When it comes to recovery of waste, which includes incineration with energy recovery, material recycling and biological treatment, the rate has been growing steadily since 1995. Since 2009 has the share been 80% or more, which means that Norway have reached the second part of the target, which was 80%. The amount of household waste sent to material recycling, including biological treatment, in 2015 was about 38%, which was an increase of 1% since the year before. If the amount that is sent to incineration with energy recovery is also included, it reaches 82%, an increase of 11% since 2014. As less waste is sent to landfills, the GHG emissions from the waste are decreasing. [environment.no, 2016] [SSB, 2016a]

## 2.3 Technologies

### 2.3.1 Waste Collection and Sorting

Waste collection includes the collection, transfer and transport of waste from the source to the treatment or disposal facility. In the book "Solid Waste Technology and Management", Nilsson states that waste collection is both the organisational and technical interface between those who generate the waste and the waste management system. [Christensen, 2011] Factors to consider are the choice of technology when it comes to waste receptables, compaction and collection vehicles. In Norway, communal, in the form of collection points or parks, curbside and entrance collection are the most common systems. Larger containers, underground containers and pneumatic systems mostly exist in densely populated urban areas in Norway, in more rural areas and in the suburbs, sacs and bins collected by a vehicle in a certain frequency are the most common solutions. In many cities in Norway, underground solutions are replacing conventional bins, but pneumatic systems are still quite rare. Underground containers can be fully or partly underground, and they are usually emptied from the bottom by specialized vehicles with cranes. Pneumatic systems can be either mobile or stationary. In the mobile system, the waste is sucked out of the storage container, usually placed underground, by a specialised vehicle. In the stationary solution the waste is, by vacuum, transported through pipes of up to 300 metres, to large storage containers that are emptied by collection vehicles. A variety of different factors influence the choice of vehicle, like number of waste types collected, size of crew needed, type of receptables, geography, and transporting distance, amongst others. [Saxegaard, 2013][Christensen, 2011]

Sorting or segregation of the waste has a great impact on the sorting efficiency and material recycling of the system, and therefore of course greatly impacts the overall performance of the system. The waste can be sorted at source or in a central sorting facility or both combined. The waste is often sorted into main waste types which contain different waste fractions. A central sorting facility can be based on different technologies like NearInfraRed-technology, optic sorting, robot sorting, mechanical heat treatment (autoclaving), enzyme treatment and sink/float technology. [Fredriksen, 2017]

### 2.3.2 Waste Treatment

**Biological treatment** of organic waste can be both aerobic, composting, and anaerobic (biogas production). The energy content in biogas is significant and it usually goes beyond the energy used in the process. The residue from the anaerobic digestion can be used as fertiliser. **Incineration** of waste is a thermal conversion with a surplus of air. This conversion releases a lot of energy and produce solid residues and flue gas. There is a wide range of technologies, from basic disposal units meant to reduce the waste volumes to modern waste-to-energy plants with emission control systems. The combustion process is highly dependant on fuel characteristics of the waste and usually the composition of the waste sent to incineration is very heterogeneous. **Landfilling** has historically been the main option for waste management. Landfills have developed from open polluting dumps to modern facilities with control measures and monitoring routines, but it is still a long-term accumulation of waste in the environment. The two main emissions from landfills that affect the environment are leachate and gas. The landfill gas is mostly CO2 and CH4, and is generated by the anaerobic degradation of organic waste. [Eurostat, 2013b] [Eurostat, 2013a] [Christensen, 2011]

**Material recycling** lets the waste substitute virgin material in the production and often saves energy and emissions in the process. In the recycling of **paper and cardboard**, the waste can be used as single raw material in the pulp or mixed in with the virgin material. Recycled paper is an important part of the raw material in the paper industry, but recycled paper will never close the material loop completely. This is due to the loss of quality and because a lot of paper mass is lost in storage in the market. **Glass** waste can be recycled in many different ways. Returnable bottles for instance, avoid much glass in the waste system. The glass waste can be remelted and used in the production of new glass products or it can be used as raw material in the production of insulation material, such as glass-wool. It can also be used as a substitute for gravel, filler and comparable components. If all contaminants are removed, there is no quality loss in the process of glass recycling. In Norway, the average content of recycled glass in glass products is around 88%. [Christensen, 2011] [Hillman, 2015]

To recycle **plastic** waste from production is a well established practice, but recycling of post-consumer plastic waste is still quite new, and is either energy recovery or material recovery. Energy is usually recovered in the form of heat, electricity or steam that substitutes primary fossil fuels. Material recovery is mechanical recycling and chemical or feedstock recycling. When recycling post-consumer plastic, foreign items and contaminants are a big problem, as disposable containers for food and beverages is an important part of the waste, and keeping the different plastic types separate is critical to maintain the qualities of plastic. Poorly separation will lead to the production of low-strength items only or the process has to go back to producing monomers, which affects the appeal of the recycling process. Recycling of **metals** is a well established practice in the metal industry, but post-consumer waste like packaging and small metal things collected from the municipal waste is often not very desirable. A lot of the metal may come from incinerators which means that it is oxidized on the surface, which lowers the quality of the material. The scrap is melted in furnaces and then tapped for direct casting or used to make alloys in a different furnace. [Christensen, 2011] [Hillman, 2015]

Several LCA studies have been done on the environmental performance of urban waste management systems and waste treatment alternatives, some of them are shortly presented here. Prognos' study on resource savings and CO2 reduction potential in waste management in Europe states that the more waste Europe recycles and recovers, the greater the CO2 emission reductions. [Prognos AG, 2008]

The WRAP report update of 2010 on the environmental benefits of recycling concludes that landfilling is the least environmentally friendly treatment alternative for both plastics and paper and cardboard. For paper and cardboard, material recycling is preferable over incineration for energy demand and water use, but comparable for climate change. The electricity mix is the key parameter in this comparison. They argue that with a lower-carbon energy mix and improved recycling technology, recycling will become favorable over energy recovery for all impact categories. The chosen energy mix was that of the UK. The same study concludes that material recycling of plastics is the best option when it comes to climate change potential, and that the environmental benefits are maximised by collection of good quality material and by replacement of virgin plastic material. As with paper and cardboard, a lower carbon energy mix will increase the advantage of recycling. The study also concludes that anaerobic treatment of organic waste is the most preferable option. [Michaud, 2010]

Østfoldforskning's report for Avfall Norge, concludes that material recycling has the lowest GHG climate impact for glass, metal and plastic waste. Biological treatment with biogas production is the preferable option for organic waste. Incineration with energy recovery has the lowest GHG climate impact for paper and cardboard. Landfilling has the greatest climate impact for all waste fractions, except for plastic- and glasspackaging. The report also states that the composition of the mixed residual waste have a great impact on the GHG emissions resulting from incineration. [Raadal, 2009]

## 2.4 Environmental Performance Criteria

The environmental performance of waste management systems is often measured in terms of material recycling, energy efficiency and/or GHG emissions. The most common way to measure environmental performance of a waste management system is through climate accounting, the net GHG emissions of the system. Most studies use this indicator, although some argue that other indicators like toxicity or water use also should be investigated. [Michaud, 2010] [Raadal, 2009] [Laitala, 2012] [Prognos AG, 2008] However, the emissions are closely linked to both material recycling and energy efficiency, therefore are these indicators shortly explained.

To measure the environmental performance of the system, the industrial ecology methods of Material Flow Analysis and Life Cycle Assessment have been used. These methods are further explaned in chapter 3.

### 2.4.1 Material Recycling

In the material recycling processes, material efficiency and material recovery ratio are important performance criteria. The EC defines recovery rates for packaging materials as the total quantity of recycled or recovered material divided by the total quantity of generated packaging material. [Eurostat, 2016]

$$\eta_{mat} = \frac{\sum X_{out,recycled}}{\sum X_{in}} \tag{2.1}$$

The degree of sorting is an important performance criteria as this greatly affects the amounts of material sent to material recycling. This can be calculated as the amount of a generated fraction which ends up in the right collected fraction, the amount of plastics in the collected plastic for instance.

### 2.4.2 Energy

In the urban waste management system, energy is consumed in all the involved processes, from transportation and collection, to the sorting and the final waste treatment. Some of the waste treatment processes produce energy, and some even have a net production of energy. Anaerobic biological treatment for instance, can often have a net production of energy. It does not take much energy to facilitate the anaerobic digestion of the organic waste, where biogas rich in CH4 and CO2 is produced. Landfills also produce a biogas that can be utilised. Incineration plants can, as described, provide heat for a district heating system or nearby industry or produce electricity. [Christensen, 2011]

There is a lot of transportation in an urban waste management system. Especially in the collection. There is also a considerable amount of transportation to the treatment facilities, as they are placed in different areas of Norway, Sweden and Germany, to mention some. Many of the material recycling processes demand a lot of energy. Metal recycling requires a lot of energy in the melting processes, but this energy demand is often lower than for the processing of virgin materials. [Christensen, 2011]

A common performance criteria for technical and industrial processes is energy efficiency or energy recovery. Energy recovery can in general be calculated using equation 2.2 [Christensen, 2011]

$$\eta_e = \frac{X_{feedstock}}{X_{process} + X_{transport}} \tag{2.2}$$

The EC defines a formula for calculating the energy efficiency for incineration facilities processing municipal solid waste, see equation 2.3 [EC, 2011]

$$Energy \quad efficiency = \frac{E_p - (E_f + E_i)}{0.97 \cdot (E_w + E_f)} \tag{2.3}$$

$E_p$ is the annual energy produced as heat or electricity. $E_f$ is the annual energy input to the system from fuels contributing to the production of steam. $E_w$ is the annual energy contained in the treated waste, based on the net calorific value of the waste. $E_i$ is the annual energy imported excluding $E_w$ and $E_f$. All are measured in GJ per year. 0.97 accounts for the energy losses due to bottom ash and radiation. [EC, 2011]

These formulas for energy recovery and energy efficiency will be taken into account for the further progress of this work, even though the later introduced performance indicators on energy will be more specific to adequately model the energy involved in transport and the energy involved and resulting from the waste treatment system as a whole (see chapter 3.4.2).

### 2.4.3 Greenhouse Gas Emissions

Greenhouse gases are gases that contribute to the greenhouse effect. This effect is responsible for the temperatures suitable for the biosphere on Earth. The sun radiates energy and most of the solar radiation penetrates the atmosphere. Some of the radiation is absorbed by the surface of the earth and then re-radiated as heat, infrared radiation. The infrared radiation is then absorbed by the molecules of the GHGs. The molecules start to vibrate and eventually they emit the radiation in all directions, where it is likely to be absorbed by another GHG molecule. The different GHGs absorb radiation of different wavelengths, depending on their absorption bands. This absorption-emission-absorption cycle keeps the heat near the surface and thus insulates the surface from the cold of space. The most important GHGs are carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O) and water vapor (H2O). [Cherubini, 2016] [Levasseur, 2015]

During the past few decades there has been a very fast increase in GHG emissions. The combustion of fossil fuels is responsible for more than two thirds of the emissions. An increase in GHGs increases the greenhouse effect and leads to climate change, a global warming of the climate system due to human activities.[Cherubini, 2016] [Levasseur, 2015] To mitigate climate change, the emissions of GHGs and especially CO2, have to be lowered, in all the sectors of society. In urban waste management systems, there are many different processes that lead to GHG emissions. Collection vehicles and other transportation in the system cause GHG emissions. In the combustion process in the incineration facility, there are emissions in the form of flue gas. This gas is usually captured and cleaned before it is released to the environment. Landfills emit gas, landfill gas, which also should be captured and cleaned before it is released into the air. In the biological treatment of organic waste, CO2 and CH4 are the main end-products. This gas is captured and then used as an energy source, substituting for fossil fuels for instance. In addition to this, all energy demanding processes cause some sort of emissions, depending on the energy source. [Christensen, 2011]

Biogenic CO2 emissions are usually considered neutral and not accounted in LCAs, as the CO2 emitted from combustion or decomposition often equals the CO2 taken up in the organism during its lifetime. [Levasseur, 2015] This is also in line with ”IPCC Guidelines for National Greenhouse Gas Inventories where it in chapter 4 ”Biological Treatment of Solid Waste” is stated that CO2 emissions of biogenic origin only should be reported as an item of information in the energy sector. [Pipatti, 2006]

Regarding GHG emissions and performance, the emissions must be quantified as the sum of emissions from individual processes in the system. The GHG emission accounts should be based on direct measurements if possible. [Christensen, 2011]

# Chapter 3

# Methodology

The structure of this master's thesis is meant to give a meaningful overview of the studied system and the modelling. The motivation for the master's thesis is given in the introduction. The general theoretical background is presented in chapter 2, which includes the results from the literature review. In chapter 4, the system in question is defined and described. In chapter 5, the main findings of the project is presented. I the next chapter, there is a discussion of the results, the work done and the method used as well as a recommendation for future work. The last chapter is the conclusion. More detailed data can be found in the appendix. The current chapter derives and explains the methodological foundation of the model as utilised and applied to the case study in the subsequent chapters.

## 3.1 Literature Review

A literature review focusing on urban waste management systems, material recycling, energy efficiency and GHG emissions in waste management systems has been conducted. The concept of urban waste systems is studied in general and the actual system of RfD has been studied thoroughly. Relevant legislation and trends in waste management in Europe and in Norway have been presented, as well as common technologies. Material recycling, energy efficiency and GHG emissions have been studied as criteria for the environmental performance of the system. The field of waste management just recently emerged to broader attention, and therefore the amount of relevant publications is comparably limited.

The references are chosen by their relation to the waste management system and/or material recycling, energy efficiency and GHG emissions. Reading material from the the course "TEP4310 Solid Waste Technology and Resource Recovery" at the Norwegian University of Science and Technology (NTNU), has been used extensively. This includes lecture notes and lecture presentations from the course and the book "Solid Waste Technology and Management". Reports and data provided by RfD have been an important basis for the modelling of the system. This material has been given through written public reports, various kinds of data collections and personal communication with Ellen Svendsvoll and

Gry Nessjøen in RfD. There has also been personal communication with Olav Skogesal in Mepex Consult AS, who conducted a climate accounting report on the RfD system. Relevant legislation and statistics have been collected from the webpages of the European Commission, Eurostat, the Norwegian government and Statistics Norway.

As far as possible have the references chosen not been older than 10 years. Other criteria were a known origin of data, published by trusted and renowned journals, organisations or official instituions or webpages. Research reports have often been chosen based on relevant waste fractions investigated.

## 3.2 Material Flow Analysis

In chapter 1.2 in the book "Practical Handbook of Material Flow Analysis", Brumer and Rechberger define material flow analysis as "a systematic assessment of the flows and stocks of materials within a system defined in space and time" [Brumer, 2004]. It is a method to describe, study and evaluate the metabolism of anthropogenic and geogenic systems. The law of conservation of matter is a very important principle in material flow analysis. A material balance of the inputs, outputs and stock is a simple way to control the results. MFA is often described as a material balance. A material can be defined as the physical matter that makes up a thing. In MFA, a process can be defined as the transformation, transport and storage of materials. A flow, or a mass flow rate, is the ratio of mass per time that flows through conductor. Typical physical units are kg/sec or t/year. [Brumer, 2004]

Transfer coefficients are very important values in MFA. They are defined for each output of a process, and multiplied by 100, they give the percentage of a total throughput of a substance. Equation 3.1 is the mathematical expression of a TC. $TC_i$ is transfer coefficient of process number $i$, $k_I$ is the number of inflows, $X_{O,i}$ is the outflow number $i$ and $X_{I,i}$ is the inflow number $i$. [Brumer, 2004]

$$TC_i = \frac{X_{O,i}}{\sum_i^{k_I} X_{I,i}} \tag{3.1}$$

Transfer coefficients are both material and technology specific and characterise the processes. They can depend on many variables, like input composition and process conditions. They are not necessarily constant, but they can be considered constant within a certain range, which makes them useful in sensitivity analysis. [Brumer, 2004]

System definition and system boundaries are very important in MFA as this is the actual object of the study. To define a system can be very difficult and demanding, but a clear definition is important for the accuracy and performance of a system, to mention a few implications. Poor MFA results is often a consequence of an unsuitable system definition. A system can for example be defined as a group of physical components connected in a way that forms an entire unit. A single process or a combination of processes can represent a system. The system boundaries are defined in time and space, and is greatly dependant on the kind of system and the research question. Data availability can also be an important factor when deciding the system boundaries. The spatial boundary is usually determined by the geographical area in which the processes are located. [Brumer, 2004]

## 3.3 Life Cycle Assessment

Life Cycle Assessment is an analysis of the environmental burdens of products, processes or services throughout the whole lifecycle, from “cradle to grave”. The LCA framework is specified in the ISO standards ISO 14040 and 14044 from 2006. The analysis has four stages:

1. Goal and scope definition,

2. Inventory analysis (LCI),

3. Impact assessment (LCIA),

4. Interpretation.

Common life cycle stages are raw material extraction, manufacture, distribution, use and end-of-life. In the goal and scope definition the purpose of the study, as well as the object, the functional unit, have to be defined. System boundaries, assessment criteria, time scale, technologies and allocation methods are also important to define. In waste management, the end-of-life phase is the primary focus of the assessment. This affects the chosen system boundaries. In the inventory analysis the raw data of the processes are investigated. In every life cycle stage the elementary flows of materials and energy are assessed. Elementary flows are the amounts of fundamental substances from and to the environment, without human processing. Hence, fundamental substances include iron, water and gases as an example. All the flows are, as far as possible, quantified in the inventory. In the impact assessment, the elementary flows are classified and characterised, that is, they are assigned to environmental impact categories. It is optional to also normalise and weigh the data. The different environmental impacts have different indicators, that can be assessed on a midpoint or endpoint level. An example can be the flow of CO2 that is assigned to the impacts indicator GWP that affects global warming, which is a common impact category. In the interpretation stage the results are interpreted and it is common to conduct a sensitivity analysis. Limitations are discussed and it is also recommended to impose a critical review of the report. [Graedel, 2015] [Christensen, 2011]

## 3.4 Generic Model Description

The model is meant to be as generic as possible, and is therefore not specialised for the RfD system. The same model was used by Pieter Callewaert and Silje Madalena Oliveira Unander to study other cases in Norway, RoAF and TRV respectively. That is also why

Microsoft Excel has been the main platform of the model, so that it can be easily used by the waste sector later, if desired. The main calculations are done in MATLAB, which is a software optimized for solving engineering and scientific problems. The language is matrix-based and is especially useful in computational mathematics. The model was developed by Pieter Callewaert in the summer of 2016 and later modified in the spring of 2017.

All relevant data for the system and the different scenarios are plotted in Excel-files. There is a main file, "Model_matlab_RfD", where all the flows and transfer coefficients in the system are defined. Other Excel-files represent the different years and for each year there are different tabs for the different scenarios. The year-files are linked to the matlab-file, in which it has to be specified which year and scenario that currently is being analyzed. Matlab reads the data from the matlab-file in Ecxel and performs the calculations. The results of the calculations are written to an Excel-file for that specific year and scenario. All the Excel- and Matlab-files can be found in appendix B, a separate attachment.

The research questions as presented in chapter 1 aim to examine the influence of measures motivated by circular economy on the material recycling rate, as well as the effect of measures for increased material recycling towards energy consumption and GHG emissions. Furthermore, critical factors of the system's environmental performance are to be identified. In order to meet these research questions, the model has been fanned out into three different layers for further examination: the material layer, the energy layer and the emissions layer, each determined by a set of performance indicators. The indicators of this system are integrated into the model by the equations or data sets as described in the following paragraphs.

### 3.4.1 The Material Layer

The material layer has been introduced to provide a view on the behaviour of material flows throughout the different scenarios within the model. It therefore contains the waste flows and fractions, as described in section 4.4. It is characterised by the performance indicators "collection efficiency", "sorting efficiency", "recycling rate" and the "company specific recycling rate". The method of material flow analysis has formed the foundation of the material layer in the model.

**The collection efficiency** is defined as "the amount of waste collected correctly over the total amount of household waste generated". Residual waste is not included in the indicator.

$$\eta_{coll} = \frac{\sum_j \sum_a X_{0a,i=j}}{\sum_j \sum_i \sum_a X_{0a,ij}} \tag{3.2}$$

where $a$ is the collection processes, $i$ is the correct collection bin for the waste fraction $j$.

**The sorting efficiency** is defined as "the amount of waste sent to recycling after sorting over the total amount of household waste generated".

$$\eta_{sort} = \frac{\sum_j \sum_i \sum_b X_{xb,ij}}{\sum_j \sum_i \sum_a X_{0a,ij}} \tag{3.3}$$

where $b$ is a vector of the final recycling processes.

**The recycling rate** is defined as "the amount of waste recycled over the total amount of household waste generated".

$$\eta_{rec} = \frac{\sum_j \sum_i (\sum_c X_{xc,ij} + \sum_d X_{xd,ij})}{\sum_j \sum_i \sum_a X_{0a,ij}} \tag{3.4}$$

where $c$ is the vector of the material markets and $d$ the vector of the bioenergy markets. This means that all the organic waste sent to the biological treatment process is recycled.

**The company specific recycling rate** is calculated with the equation that follows

$$\eta_{comp} = \frac{\sum_j \sum_i \sum_e X_{xe,ij}}{\sum_j \sum_i \sum_a X_{0a,ij}} \tag{3.5}$$

where $e$ is the vector of the processes to which the company sends its waste.

### 3.4.2 The Energy Layer

The second layer is the energy layer, and it is based on the life cycle assessment methodology. It subsumes two components: the energy involved and used by transportation within the flows and furthermore the energy that is involved and produced by the system. Both of which are determined by a set of the following performance indicators:

#### A Transportation

The calculation of energy use and emissions form transportation are based on the following equations in line with CLECAT's guide for calculating GHG emissions. [Schmied, 2012]

**The energy consumption of the transport**

$$EC_{f,t,i}(\frac{kWh}{yr}) = RD_{f,t,i}(km) \cdot CF_{t,i}(\frac{1}{yr}) \cdot EC_f(\frac{l}{km}) \cdot E_f(\frac{kWh}{l}) \tag{3.6}$$

where $EC$ is energy consumption, $RD$ is route distance, $CF$ is collection frequency and $E$ is energy content. $f$ is the specific fuel type, $t$ is the collection technology and $i$ is the waste type.

**The energy intensity of the transport**

$$EI_{f,t,i}(\frac{kWh}{tkm}) = \frac{EC_{f,t,i}}{W_{f,t,i}(\frac{t}{yr}) \cdot RD_{f,t,i}(km)} \tag{3.7}$$

where $tkm$ is tonne per kilometer, $EI$ is the energy intensity and $W$ is the weight.

**The transport energy**

$$TE_{ab,i,f}(\frac{kWh}{yr}) = EI_{f,t,i}(\frac{kWh}{tkm}) \cdot W_{f,t,i}(\frac{t}{yr}) \cdot D_{ab,i}(km) \cdot S_f \tag{3.8}$$

where $TE$ is the transport energy from process $a$ to process $b$. $S$ is the share of the total $tkm$ that has been collected with fuel type $f$.

More information on the values used in these calculations can be found in the transportation section in appendix A.

## B Process energy

**The process energy**

$$PE_{p,i,f}(\frac{kWh}{yr}) = W_{f,t,i}(\frac{t}{yr}) \cdot ER_{p,i,f}(\frac{kWh}{t}) \tag{3.9}$$

where $PE$ is the process energy for process $p$, waste type $i$ and energy carrier $f$. $ER$ is the energy requirement of the process.

**The energy out of the system**

$$Eo_{ij}(\frac{kWh}{yr}) = Win_{ij}(\frac{t}{yr}) \cdot LHV_i(\frac{kWh}{t}) \cdot EE \tag{3.10}$$

where $Eo$ is the energy out of the system, $Win$ is the waste inflow, $LHV$ is the lower heating value and $EE$ is the energy efficiency.

**The biogas out of the system**

$$Bo_i(\frac{kWh}{yr}) = Win_i(\frac{t}{yr}) \cdot MY_(\frac{Nm^3}{t}) \cdot LHV_i(\frac{kWh}{Nm^3}) \tag{3.11}$$

where $Bo$ is the biogas out of the system, $Win$ is the waste inflow, $LHV$ is the lower heating value and $MY$ is the methane yield.

**The overall energy efficiency**

$$\eta_{energy} = \frac{Bo + Eo}{TE + PE + C} \tag{3.12}$$

where $\eta_{energy}$ is the energy efficiency and $C$ is the calorific value of the waste input.

More information on the values used in these calculations can be found in the energy section in appendix A.

### 3.4.3 The Emission Layer

To adequately consider the emissions within the model, the emission layer makes use of empirical data as collected from Ecoinvent and Østfoldforskning among others, providing the average CO2 emission factors for different processes and energy carriers. The following values have been integrated into the model:

**Table 3.1:** Emission factors connected to energy carriers in sorting and transport.

| Energy carrier | Kg CO2e./kWh | Reference |
|---|---|---|
| Heavy fuel oil | 0,3413 | [Frischknecht, 2005] |
| Diesel | 0,2732 | [Schmied, 2012] |
| Natural Gas | 0,2577 | [Frischknecht, 2005] |
| Heat | 0,1390 | [Løseth, 2011][SSB, 2017] |
| Electricity (NO) | 0,0441 | [Frischknecht, 2005] |
| Biogas | 0,0000 | Biogenic emissions |

**Table 3.2:** Emission factors connected to incineration and recycling of the different waste fractions.

| Waste fraction<br>- | Incineration<br>(kg CO2e./kg) | Recycling<br>(kg CO2e./kg) |
|---|---|---|
| Glass | 0,0244 | 0,857 |
| Metal | 0,0190 | 0,051 |
| Organic | 0,0310 | 0,006 |
| Residual waste | 0,5046 | - |
| P & C | 0,0245 | 0,672 |
| Plastics | 2,3478 | 0,666 |
| Hazardous | 1,4279 | - |
| Textiles | 0,1454 | - |

The incineration factors in table 3.2 are collected from Ecoinvent and the CO2 factors for recycling are collected from Østfoldforskning. [Frischknecht, 2005] [Raadal, 2009]

**Table 3.3:** Avoided emission factors.

| Waste fraction | Emissions | Unit |
|---|---|---|
| Glass | -0,895 | kg CO2e./kg |
| Metal | -2,589 | kg CO2e./kg |
| P & C | -0,976 | kg CO2e./kg |
| Plastics | -1,783 | kg CO2e./kg |
| Organic | -0,273 | kg CO2e./kWh |
| Residual waste | -0,160 | kg CO2e./kWh |

The avoided emission factors in table 3.3 are collected from Østfoldforskning. [Raadal, 2009]

## 3.5 Case Study

As a next step of the methodological approach of this work, this generic model has been applied and tested within a case study. The subject of this case study is the waste treatment system of the waste management company RfD. First, the model has been applied and adjusted based on the data as provided by the company for 2015, to adequately represent the current situation. Based on this empirical foundation, the now fitted to the company model has been utilised to calculate different future scenarios based on the performance indicators within the different layers as described above. Those steps, the different scenarios and the detailed characteristics of the case study are described in the following chapter.

# Chapter 4

# Case Study Description

## 4.1 RfD

RfD is responsible for the collection of municipal solid waste in the nine municipalities Drammen, Hurum, Lier, Modum, Nedre Eiker, Røyken, Sande, Svelvik og Øvre Eiker. They consist of around 80 000 households and 5 000 cabins. The company is a publicly funded organisation, which can not make a profit of the services delivered to private households. RfD is an ordering organisation, which means that the production is set out on public tenders to private operators. In this context the production is managing collection trucks, operation of collection facilities and inspection of collection points. RenoNorden is in charge of the collection of the waste and Lindum is operating the different collection centres. During 2015 RfD closed down all their public collection points, and now only operates with collection at source and collection centers/parks. In the region there is a total of seven collection centers.

The system is defined by the 17 areas or processes, but the main focus is on the 12 fundamental processes of the waste treatment system (see figure 4.1). RfD is responsible for processes 1-5, but process 2 and 3 are not a part of the system of 2015. Process 3, collection at points, was as mentioned phased out during 2015. Process 2, central sorting, is likely to be a part of the system some time in the future and is therefore modelled in one of the scenarios in year 2030. RfD responsibilities are marked in green on the flowchart, see figure 4.1. Most of the processes take place in Norway, among others that involve Sweden and Germany

The receptable technologies in use in the system are small containers, larger containers, underground containers and pneumatic systems. Underground collection solutions are not standard in the region, but developers can apply for an approval from RfD to use such systems. Per 25.06.2017 there are no stationary or mobile pneumatic collection systems in the region. But, this can be a solution in the future for new large urban areas or in rehabilitation of densely populated areas in the city centres. [RfD, 2016]

## 4.2 System Boundaries

The temporal boundary of the system is the years 2015, 2025 and 2030. The system in 2015 is considered the basis for the model, and represents the *reference scenario*. The geographical boundaries are difficult to define exactly. Some of the processes included in the system, is set in the Drammen region and the nine municipalities in RfD's responsibility. This boundary is marked with a dashed green line in the flow chart in figure 4.1 Most of the processes take place in Norway, but some processes, especially the treatment facilities, are in Sweden and Germany. The system boundaries have therefore been chosen in a way that includes the most important processes, marked in a red dashed line in the flow chart. Processes and flows marked in grey, are not a part of today's system. The system is characterised as an open system, as it interacts with its surroundings.

## 4.3 Processes

The main processes inside the system boundaries are:

1. Collection at source
2. Central sorting
3. Collection at points
4. Reloading/storing
5. Collection at parks
6. Sorting and packing
7. Biological treatment
8. Incineration
9. Final recycling facility
10. Landfill
11. Bottom ash treatment
12. Final recycling facility, BAT
13. Fertiliser production
14. Material production, BAT
15. Material production
16. Energy market, biological treatment

17. Energy market

The processes outside the system are given the number 0, the households is a process like this.

## 4.4 Main Waste Flows and Fractions

The main waste flows are:

- Glass and metals (G&M)
- Organic Waste (Org.)
- Residual waste (Rest.)
- Paper and Cardboard (P&C)
- Plastics (Plast.)

The main fractions under consideration are:

- Glass
- Metal
- Organic waste
- Residual waste
- Paper and cardboard (P&C)
- Plastics
- Hazardous waste/waste from electrical and electronic equipment (WEEE)
- Recyclable textiles

In figure 4.1 all the 17 processes are represented as squares. Some processes contain all the waste flows, but most of them only contain some waste flows or even some fractions of some waste flows. The arrows linking the different processes represent transfer coefficients as well as transportation.

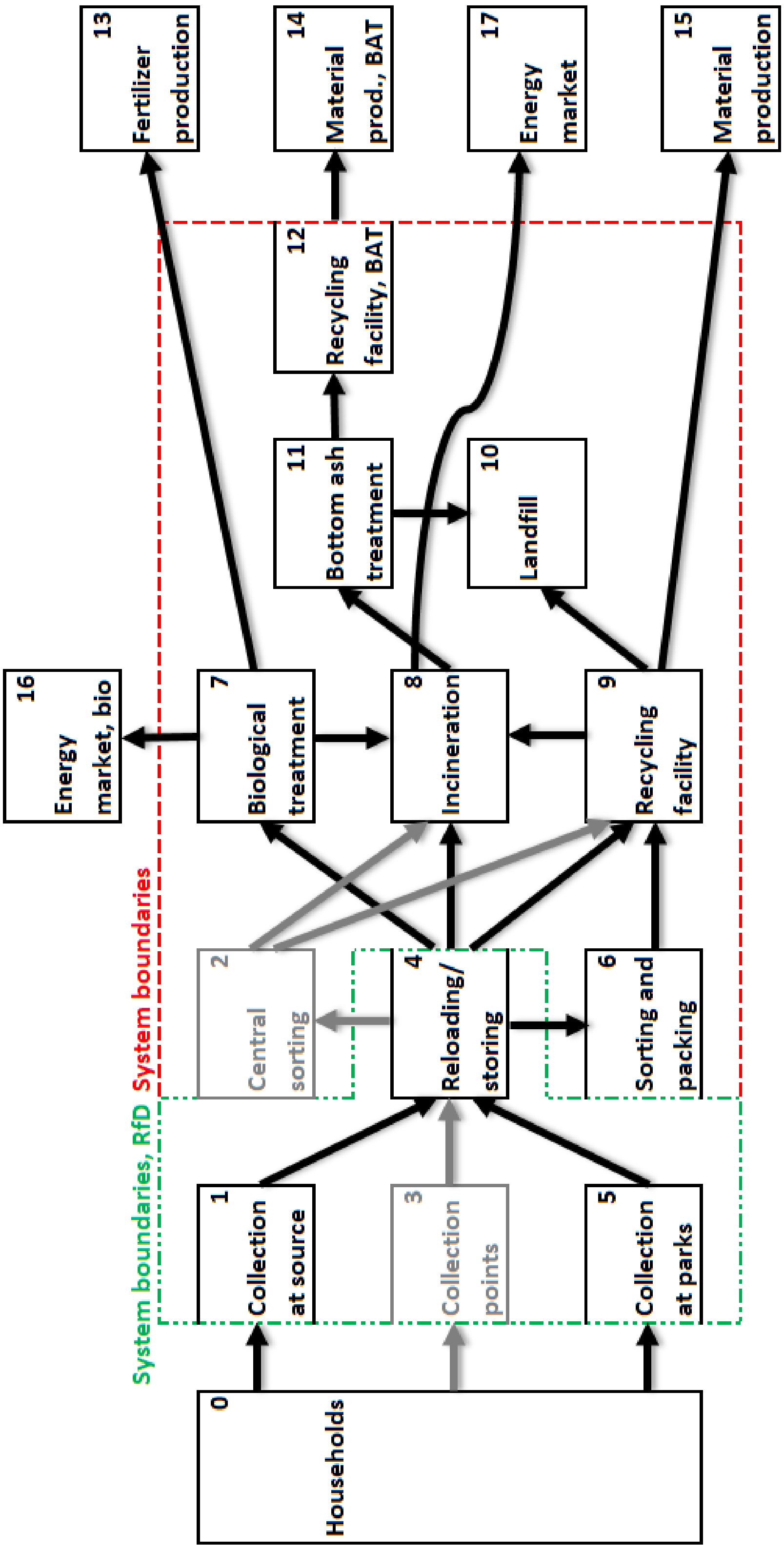


**Figure 4.1:** The flow chart used in the model.

## 4.5 Transportation

Between all the processes in the system, there is transportation, as shown with arrows in figure 4.1 on the previous page. The transportation distances between processes 1 to 5, apart from 2, of the system are based on actual data from RfD, but the further downstream you go in the system, the more distances are based on average or general numbers and assumptions.

## 4.6 Scenarios

Table 4.1 shows the different scenarios investigated in the model for each year.

**Table 4.1:** Scenarios investigated for the different years.

| 2015 | 2025 | 2030 |
|---|---|---|
| Reference scenario | Reference scenario | Reference scenario |
| | More underground | More underground |
| | Biogas | Biogas |
| | | Central sorting |
| | | All scenarios |
| Perfect sorting | Perfect sorting | Perfect sorting |

### 4.6.1 General Assumptions for all Scenarios

Prognosis for the population in the region is shown in figure 4.2. The blue line is the case of high national growth, the green line is medium national growth and the red line is low national growth. The figure is taken from the report "Fremtidens kildesortering i Drammensregionen" and the prognosis is based on calculations made by Asplan Viak with data from SSB [RfD, 2012]. On the basis of this graphic, the population is assumed to be 228 000 people in 2025 and 235 000 in 2030, following the medium national growth.

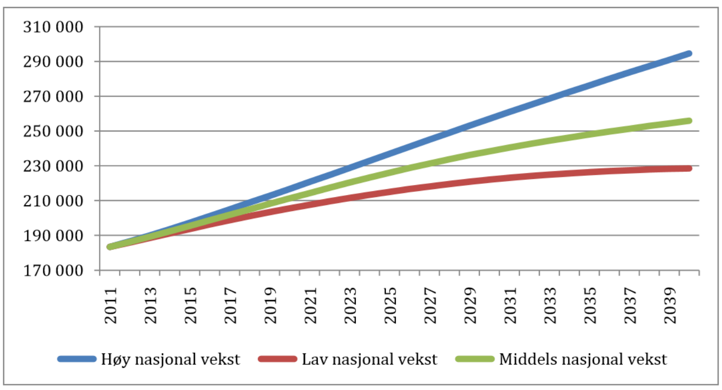


**Figure 4.2:** Population prognosis for the region [RfD, 2012].

The increase in waste amounts is also based on calculated results from "Fremtidens kildesortering i Drammensregionen". In this report from 2012, it is estimated that the waste amount in 2020 will be 41% higher than in 2012 [RfD, 2012]. This means an increase of 5,125% each year. In 2025 this means an increase of 51% from 2015 levels and in 2030 an increase of 77%. The relative material composition of the municipal waste was assumed to stay the same, in line with literature. [Lindhqvist, 2009]

All scenarios include the material layer, energy layer and emissions layer, as presented in chapter 3.4, for every calculated year.

### 4.6.2 The Reference Scenario

The *reference scenario* is the situation of the modelled system in the year of 2015. Necessary data has been collected mostly from RfD and Mepex Consulting AS. Where data was not available, assumptions have been made. The *reference scenarios* of 2025 and 2030 are based on the business as usual principle. The only factors changed in these scenarios are a growth in population and an increased amount of waste generated. Key data of the *reference scenario* in 2015 is provided in table 4.2. The waste amounts are given in tonnes and the amounts include the defined waste fractions in the system, all other fractions are left out of the system. The total amount of waste collected in the system is therefore higher in reality.

**Table 4.2:** Key data of the system in 2015.

| | |
|---|---|
| Population | 194 425 |
| Total amount of waste generated at households | 51 042 |
| Total amount of waste generated at collection parks | 13 350 |

RfD collects five different waste types, the selected main waste flows, from the households. Figure 4.3 shows the waste fractions found in the different waste bins and the degree of sorting. This degree of sorting has been assumed for the small and larger receptables, but not for the underground solutions.

Based on data provided by RfD, the percentages of collection technologies were assumed as given in table 4.3. This assumption was based on the distribution of houses and apartment buildings in the area [Bratland, 2013b] [Bratland, 2013c] [Bratland, 2015]. Single family houses were assumed to have small single collection containers and apartment buildings were assumed to have either larger containers or a sort of underground solution.

### 4.6.3 The More Underground Scenario

The *more underground* scenario has the same characteristics as the *reference scenario*, except for the assumption that a larger part of the receptables are assumed to be underground which implies both stationary as well as mobile solutions.

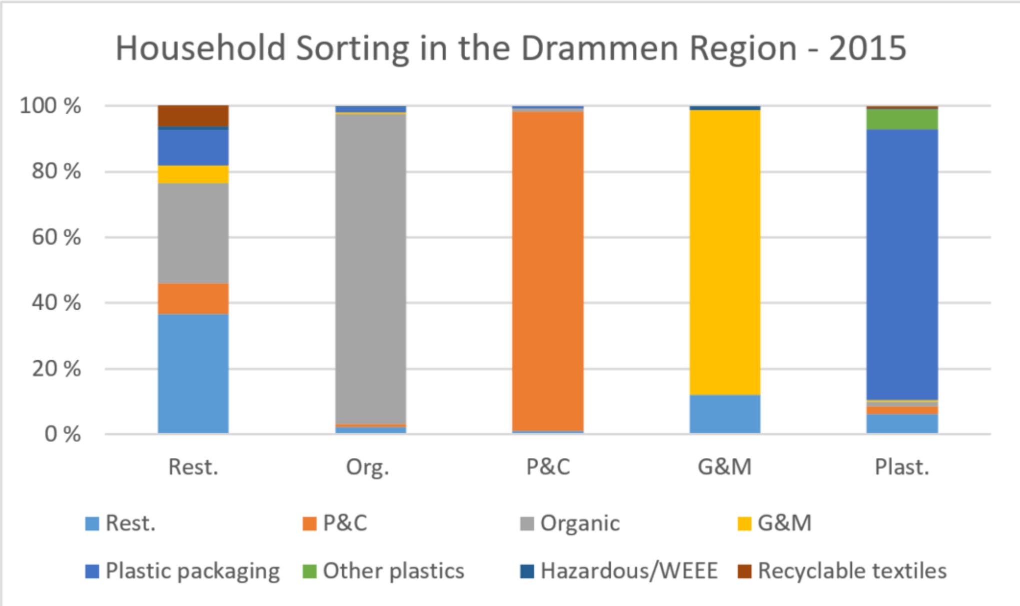


**Figure 4.3:** Household sorting in the Drammen region in 2015.

**Table 4.3:** Percentage of collection technologies in the different scenarios.

| Collection technology | Reference scenario | More underground scenario |
|---|---|---|
| Small containers | 60% | 60% |
| Larger containers | 35% | 10% |
| Underground containers | 5% | 20% |
| Pneumatic solutions | 0% | 10% |

Underground systems for the collection of waste flows have grown in importance and dissemination especially within the past two decades. In comparison to conventional surface container solutions, these systems are positioned sub-surfaced in pre-fixed positions. They can either operate as stand-alone collection points or be integrated in a stationary pneumatic collection system. They are then connected to a centralised facility (for further processing), while the waste gets transported pneumatically [ISWA, 2013] [Saxegaard, 2013]. In this work, both types are regarded as separate variables in the scenario (see table 4.3).

Both types of systems, underground containers as well as pneumatic solutions, are considered technologies suitable to improve the logistics in waste management and contribute to sustainability. They create new potential for automation and therefore a decrease of required workforce or involved collection vehicles, reduce the dependency on climate conditions, contribute to a more efficient use of available space especially in densely populated areas, where they also offer better hygiene especially compared to larger containers, whereas installation and maintenance may imply higher costs. [ISWA, 2013] [Brattebø, 2016a]

Based on these observations, the availability of underground containers as well as pneumatic solutions is chosen as a scenario that needs to be considered, since RfD will consider broader use of these systems for the future. Since a large part of the examined region with its nine municipalities is not characterised by dense population, the usage of underground containers and pneumatic solutions is just moderately changed from 5% to 20% and 0% to 10%

respectively (see table 4.3). The degree of sorting in the underground collection solutions, bottom emptied containers and pneumatic systems, was assumed to be slightly lower than for smaller containers. This assumption was based on several picking analyses done by both RfD and TRV [Bratland, 2013b] [Bratland, 2013c] [Bratland, 2015] [Bratland, 2013a] [Syversen, 2016]. See appendix A for further information on the degree of sorting.

### 4.6.4 The Biogas Scenario

By the end of 2017, all of the collection vehicles used in RfD's system will be fuelled by biogas. This was one of the scenarios that RfD requested to be investigated. RenoNorden supplies the vehicles and is responsible for the collection of the household waste. The data for the collection vehicles is presented in table A.2 in the appendix. It is assumed that only the collection vehicles that collect waste from the households are fuelled by biomethane, all other vehicles in the system is still assumed to be fuelled by diesel. Consequently is it only the transport from the households to the reloading stations that is affected in this scenario. See appendix A for further information about the calculation of energy consumed in the transportation. Emissions from biogas are in this thesis set to 0, as explained in chapter 2.

### 4.6.5 The Central Sorting Scenario

RfD is, together with RiG and VESAR, looking into the possibility of a shared central sorting facility. The provisional report evaluating this opportunity is based on the situations of the three companies as well as experience and results from RoAF's central sorting plant. As this plant is evaluated and modelled by fellow student Pieter Callewaert, this scenario is largely based on data from his communication with RoAF as well as this provisional report. As a central sorting facility is not a definite part of RfD's future plans, has this scenario only been investigated for the year of 2030.

The provisional report states that there is reason to believe that a central sorting facility will increase the material recycling in the system, especially when it comes to plastic packaging, but also incorrectly sorted paper and metal. The central sorting facility will sort residual waste and plastc waste, and it is also possible to stop the household sorting of organic waste and sort it out with the residual waste. The central sorting facility in question has NIR-technology. [Fredriksen, 2017]

In this scenario it is assumed that the plastic is no longer sorted at source, but sent with the mixed residual waste to the central sorting facility. The organic waste is still sorted separately, as was recommended in the provisional report. [Fredriksen, 2017] This leads to less organic waste in the sorting facility which means less contaminated plastic in the waste. It is therefore assumed a higher degree of sorted plastic waste than what has been assumed for RoAF's sorting facility. This scenario, as well as the *all scenarios* scenario, it therefore modelled with a sorting of 50% of the plastic waste, which is 14% higher than RoAF's facility. [RoAF, 2017]

### 4.6.6 The All Scenarios Scenario

This scenario combines the *more underground*, the *biogas* and the *central sorting* scenario. This was done to see the impacts of the combined measures of the other scenarios, and it is also likely that this will be closer to the actual future situation.

### 4.6.7 The Perfect Sorting Scenario

In this scenario it is assumed perfect sorting at source, the households. This means that all the waste fractions are sorted correctly to the right waste flow. Textiles and hazardous waste are assumed sorted correctly when sorted into the mixed residual waste, the rest type. This represents a highly theoretical situation, but has been modelled to get an impression of sorting as a factor for environmental performance of the waste management system. This scenario have been modelled for all the years investigated.

# Chapter 5

# Results

The following chapter presents the results as calculated by the used model. The results will be shown in graphs, explained and summarized for the subsequent discussion. First, the results of the *reference scenarios* after calculating it for 2015, 2025 and 2030, will be presented by examining the results for each of the three layers (material, energy and emissions), to have the required reference for comparing the variations of the other five scenarios. Second, the results of each of these different scenarios will be presented, before the results will be put into context and comparison with each other in section 5.7. Especially the findings and observations from that step will form the foundation for the following discussion as conducted in chapter 6.

## 5.1 The Reference Scenarios

The results from the modelling show that the conditions of the system stay the same throughout the years for the *reference scenarios*. The relationship between the different fractions and treatment methods stays the same. This was expected, as the only parameters that was changed, was the population and the total waste amounts. The growth was applied to all the different fractions and collection technologies in all scenarios. It is therefore not necessary to present all the results of the *reference scenarios*. The results from the modelling of the *reference scenario* in the year of 2015 is presented thoroughly as it represents the actual situation of the waste management system of RfD.

Table 5.1 shows the generated amounts collected from households and at collection parks. The largest collected waste type by weight is rest, with almost 35 000 tonnes. The weight of the rest fractions that belongs in the rest waste is around 19 000 tonnes, which is the largest waste fraction by weight, but still considerably less than what is collected as rest. It is generated more than 18 000 tonnes of organic waste, but only around 10 000 tonnes collected in the bin for organic waste. For plastics only around half of the generated plastic waste is sorted into the plastic waste bin at the households. Glass and metal, and especially paper and cardboard seems to be the waste types with the most correct sorting in the households.

**Table 5.1:** The generated waste amounts from the households in tonnes for the *reference scenario* in 2015

| Generated Waste Amounts (t/yr) | | | | | | |
|---|---|---|---|---|---|---|
| | G&M | Org. | Rest. | P&C | Plast. | **Total** |
| Glass | 1753 | 28 | 1041 | 14 | 5 | 2842 |
| Metal | 877 | 14 | 520 | 7 | 3 | 1421 |
| Organic | 0 | 10018 | 8206 | 84 | 20 | 18328 |
| Rest. | 391 | 257 | 15346 | 126 | 176 | 16296 |
| P&C | 0 | 106 | 3577 | 12538 | 38 | 16259 |
| Plastics | 0 | 170 | 3215 | 156 | 2855 | 6397 |
| Hazardous | 38 | 43 | 660 | 0 | 4 | 745 |
| Textiles | 0 | 0 | 2148 | 0 | 11 | 2160 |
| **Total** | 3058 | 10636 | 34713 | 12926 | 3114 | 64447 |

### 5.1.1 Material Recycling

Figure 5.1 shows the collection-, sorting- and recycling efficiency of the system. These efficiencies are calculated with the equations shown in chapter 3. The metal fraction has the by far highest material recycling efficiency. Paper and cardboard and glass also have high material recycling rates. The plastics fraction has the lowest material recycling efficiency of only 34%.

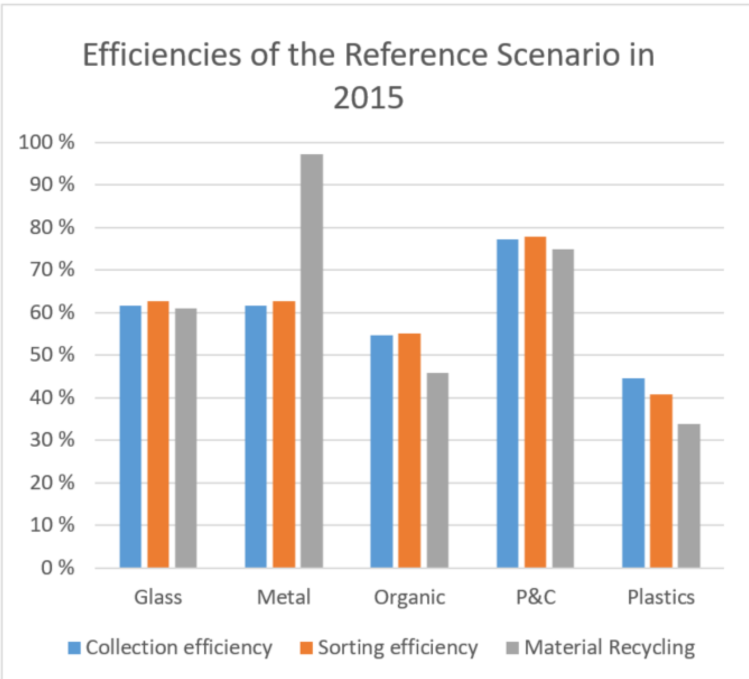


**Figure 5.1:** The collection-, sorting- and recycling efficiency for the waste fractions in the *reference scenario* in 2015.

### 5.1.2 Energy

Table 5.2 shows the energy flows of the system. The first three rows are the inflows and the last row is the energy leaving the system boundaries. The overall system has a net consumption of energy of 398 GWh. Most of the energy enters the system as feedstock energy, energy stored in the waste. Parts of this energy is recovered through incineration and the production of biogas. 88% of the energy production is a result of incineration, and of this 78% is produced as heat. The rest of the energy produced in the system is produced as biomethane in the biological treatment.

**Table 5.2:** The energy flows of the system in the *reference scenario* 2015.

| **Energy [kWh]** | | **Share of total** |
|---|---|---|
| Feedstock | 4,24E+08 | 90% |
| Transport | 2,10E+07 | 4% |
| Process | 2,64E+07 | 6% |
| Produced | 7,33E+07 | |

Figure 5.2 shows the total energy consumption of the transport in the system. The four columns in the far left in the figure is the collection energy for each collection technology. The fifth column, the second highest in the figure, is the energy consumed by transporting waste from the households to the collection parks. This is done by personal vehicles. On average the transported amount is 145 kg, the transport distance is 14 km and the number of visits, the collection frequency, is 91584 per year. All these numbers were calculated averages connected to the household waste based on data from RfD. This means that the relative energy intensity of this transport is very high, compared to the energy intensity of the transport in the rest of the system. The largest share of the consumption of energy is in the transport of waste to incineration.

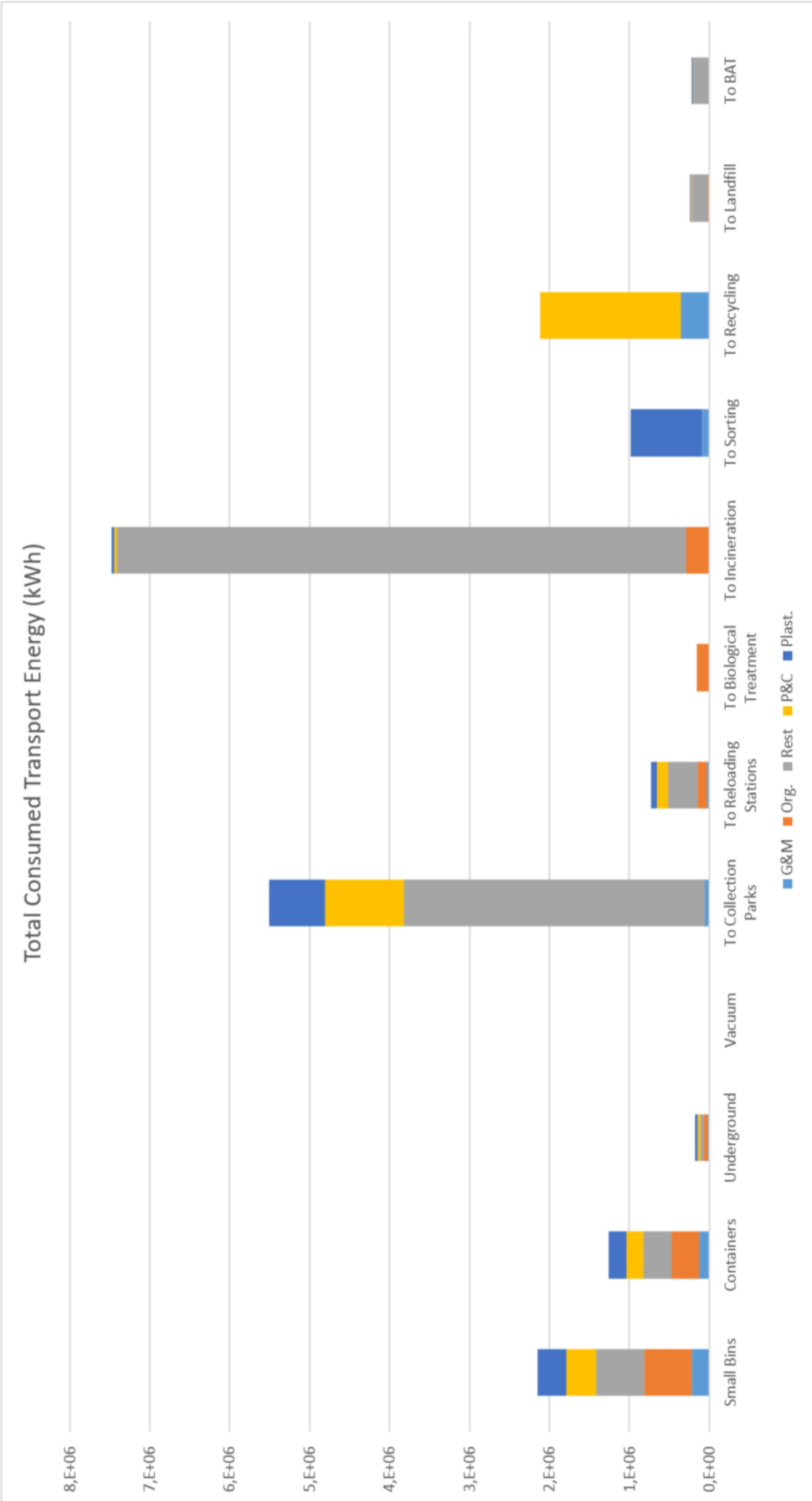


**Figure 5.2:** The total consumed transport energy in the *reference scenario* in 2015.

### 5.1.3 Emissions

Figure 5.3 shows the emissions in kg CO2-equivalents resulting from the collection of the waste and the transport to the reloading stations of RfD. The by far largest part of the emissions are caused by the transport of waste from the households to the collection parks. This corresponds to the energy consumption shown in figure 5.2. The transportation of waste from the households to the collection parks accounts for 56% of the emissions for the overall collection and transportation to reloading stations and 26% of the emissions of the total transportation in the whole system.

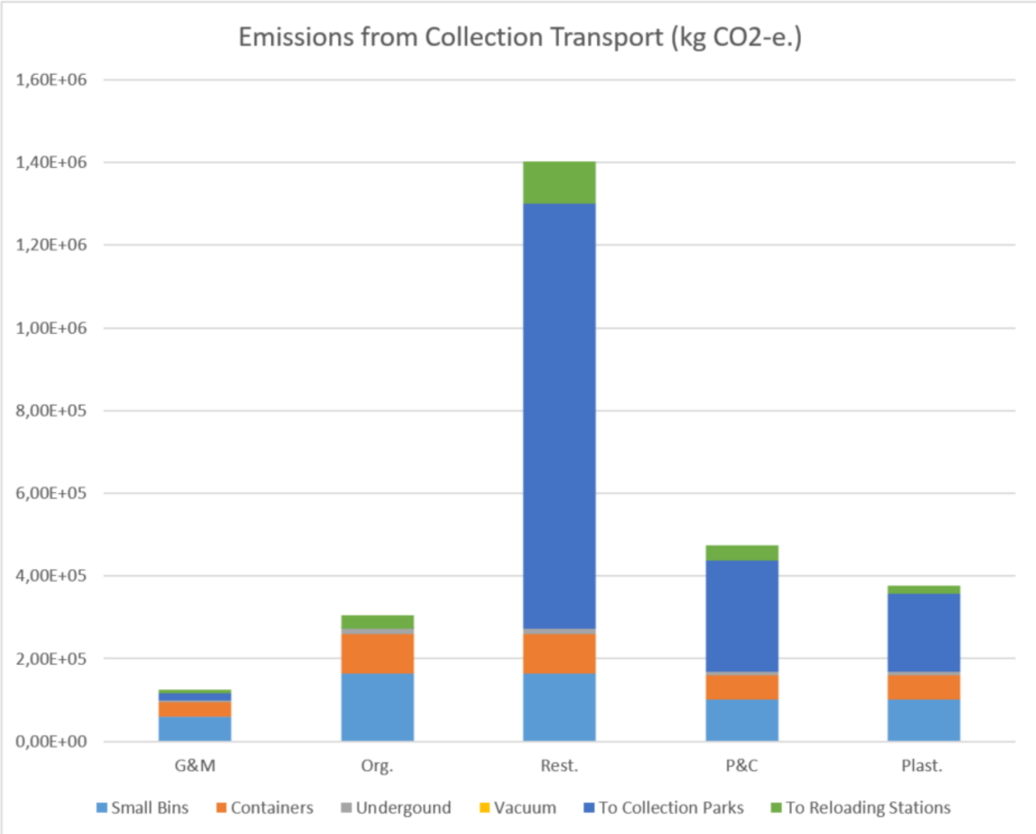


**Figure 5.3:** The emissions in kg CO2-equivalents from the collection transport of RfD in the *reference scenario* in 2015.

The total emissions in kg CO2-equivalents per waste type is shown in figure 5.4. Avoided emissions as a result of activities in the system that replaces other activities, such as avoided material production through material recycling, or avoided energy production through energy recovery, is shown as negative emissions in the figure. This means that negative emissions have a positive climate impact on the environment. The waste type with the highest amounts of avoided emissions is paper and cardboard, followed by rest. The process that contributes the most to the emissions is incineration, followed by material recycling. Most of the incineration is connected to the rest waste flow and most of the emissions from recycling are connected to paper and cardboard.

Figure 5.5 shows the emissions in kg CO2-equivalents per inhabitant and waste fraction. The figure shows that most of the avoided emissions are the result of avoided material

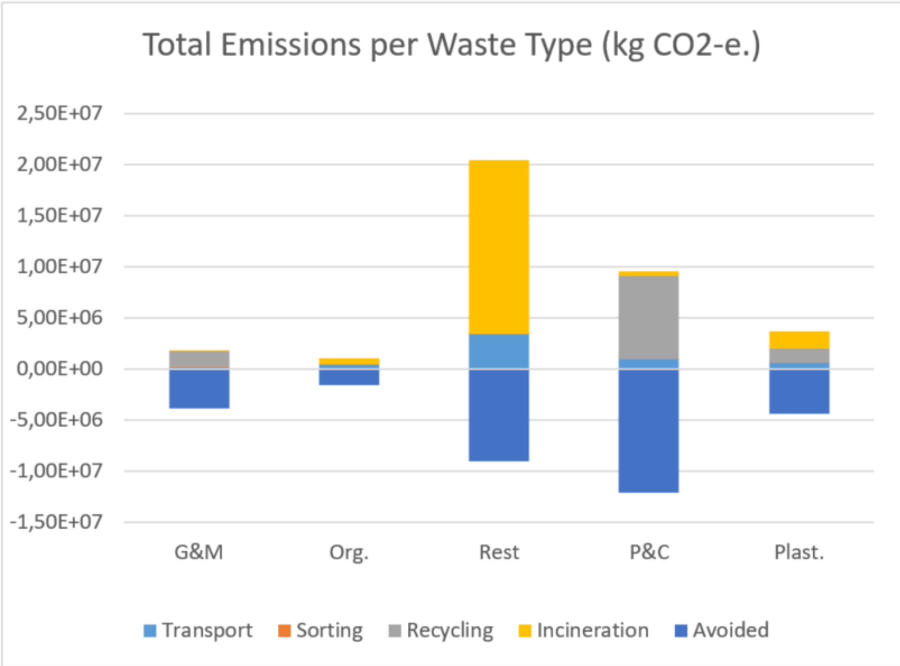


**Figure 5.4:** The total emissions in kg CO2-e. per waste type in the *reference scenario* in 2015.

production. Avoided energy production also contributes to avoided emissions, especially for the organic and rest fractions, but also for the plastics fraction. As in figure 5.4, incineration is the main contributor to emissions. For the plastics fraction, is it only a small share of the emissions resulting from material recycling, most of the emissions are caused by incineration. Metal, organic and paper and cardboard all have net negative impacts of around 20 kg CO2-equivalents. The glass fraction is close to neutral. The plastics fraction have the highest net impact of 25 kg CO2-equivalents, while the rest fraction have a net impact of 17 kg CO2-equivalents.

The net climate impact in CO2-equivalents pr kg collected as the different waste types is shown in figure 5.6. A negative value implies that the activities of the system avoids more emissions than they emit connected to that specific waste flow. According to this, glass and metal have the relative most positive impact on the environment. All waste types apart from rest, have a negative net climate impact. Paper and cardboard, and plastics have the same net climate impact per kg collected.

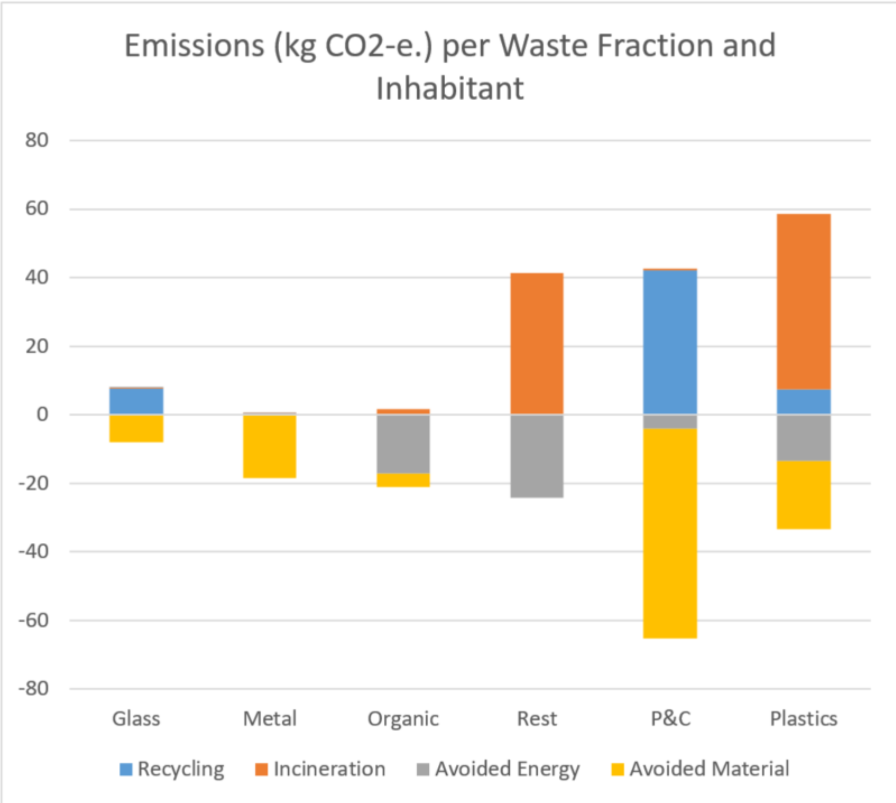


**Figure 5.5:** The emissions in kg CO2-e. per inhabitant per waste fraction in the *reference scenario* in 2015.

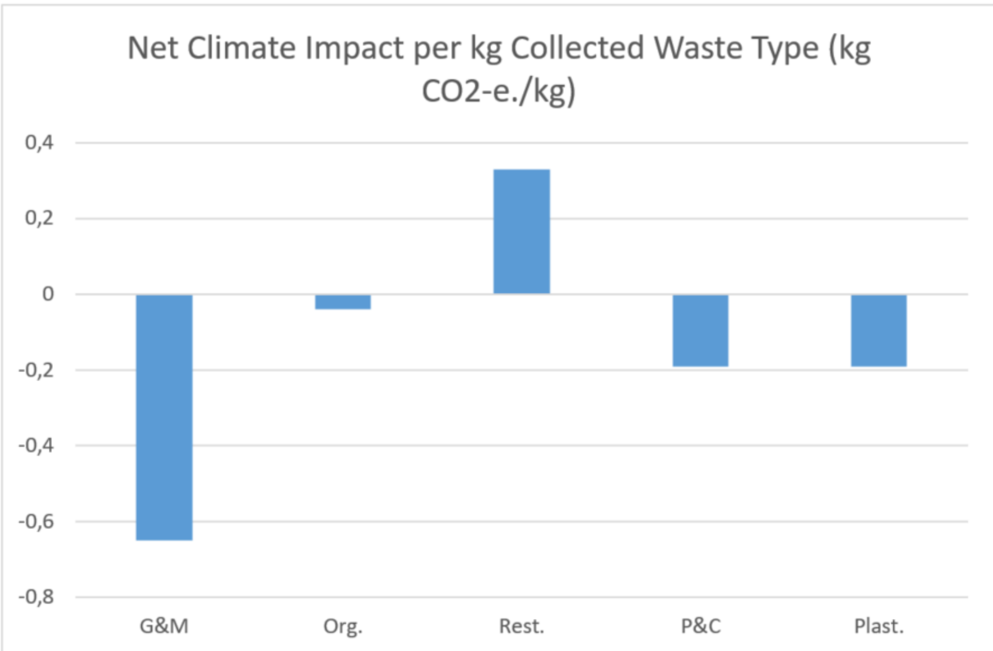


**Figure 5.6:** The net climate impact in kg CO2-e. per kg collected as the different waste types in the *reference scenario* in 2015.

## 5.2 The Perfect Sorting Scenarios

As the *perfect sorting* scenarios behave very similar over time, it is only the results from the year 2015 and how they differ from the*reference scenario* in the same year, that is presented shortly. As the sorting in the households is assumed perfect the collection-, sorting-, and material recycling efficiencies are higher for all waste fractions in this scenario than in the *reference scenario*. The most striking difference is seen for the plastics fraction, where the material recycling efficiency increases from 34% to 76% in this scenario. See figures in chapter 5.6.1 for more details. 51 % of the generated waste is now sent to energy recovery, only 4% is sent to landfills and 45% of the generated waste has material recycling as the final destination. This is an important change from the *reference scenario* where 58% was sent to incineration, 11% to landfills and 31% to material recycling. As more plastic waste is sent to material recycling, rest remains the only fraction with a positive value for the net climate impact, see figure 5.23 in chapter 5.7.3.

## 5.3 The More Underground Scenarios

The *more underground* scenarios behave very similar in year 2025 and 2030, consequently is it only the results from year 2025 that is presented shortly. The results show that there is a difference between the degree of sorting compared to the *reference scenario*. The collection-, and sorting efficiencies are lower for all fractions. Nevertheless, the delta never exceeds 1.5% and can therefore be considered as not relevant. Hence the numbers show, that a higher implementation of underground containers and pneumatic solutions do not have an impact on the sorting. This has been expected, since the sorting in the different collection technologies is very similar for the end user/consumer. The difference in the sorting also leads to a small difference in the destinations of the waste fractions, but overall are the conditions of the two scenarios very comparable. The slight change in collection technology also affects the energy intensity of the collection transport from the households. On the overall total of the system this means very little, as the transportation in general is around 4 % of the total energy use of the system and 15% of the total emissions.

## 5.4 The Biogas Scenarios

As the only change in these scenarios compared to the *reference scenarios*, is that the collection vehicles are fuelled by biogas, the material flows stay the same. The only changes are found in the energy layer and in the emission layer of the model. The *biogas scenario* has lower emissions for the collection transport, as these emissions come from biomethane and therefore are not counted in accordance with common LCA practice.

The consumed energy of the collection in the system, is also different compared to the *reference scenario*. This is because vehicles fueled by biogas have a different energy intensity than vehicles that run on diesel. The energy consumption in kWh of the collection is higher in this scenario than in the *reference scenario*. The energy consumption of the collection transport from the households have an increase of 88%. The main contributor to both the energy consumption and the emissions of the collection is still the personal vehicles driven to the collection parks, but the collection vehicles now make up a larger share of the total energy consumption.

## 5.5 The Central Sorting Scenario

The results of the *central sorting* scenarios are compared to the *reference scenario* in year 2030. The central sorting facility increases the sorting efficiencies of the metal, paper and cardboard, and the plastics fraction. The increase is 35% for metal, 9% for paper and cardboard and 12% for the plastics fraction. 35% of the waste is now material recycled, compared to 31% for the *reference scenario*. The material recycling efficiency for the metal fraction is unchanged, but the material recycling efficiency increases with 9% for paper and cardboard and 11% for plastics. This leads to lower emissions connected to the plastics fraction and a higher amount of avoided emissions for the whole system. The net climate impact for the rest type is significantly lower, but it is higher for the plastic waste flow, see chapter 5.7 and especially figure 5.24.

## 5.6 The All Scenarios Scenario

The results of this scenario are very similar to the results of the *central sorting* scenario. The changes seen in the *more underground* and *biogas* scenarios are also present in this scenario, but as those results had a relatively small impact on the overall system, the changes connected to the central sorting facility are the most striking. Apart from the strictly theoretical perfect sorting scenario in 2030, this scenario has the overall lowest climate impact. See chapter 5.7 for more detailed results.

## 5.7 Comparison Across Scenarios Over Time

In this section the main results and critical factors of the waste management system is shown for all the different scenarios over time. This is done to see the development and differences between the years and scenarios, and to better identify important areas for improvement. The results concerning the material flows are presented first, then the energy results follow and lastly the findings connected to emissions are presented. The results are mainly presented in figures and shortly explained. The figures provide a great overview of the results and make the comparison across scenarios, years, waste fractions and flows easier. Further results can be found in appendix B.

### 5.7.1 Material Recycling

The following figure, figure 5.7, shows the final destinations of the household waste of RfD for the different scenarios over time. The scenarios that stand out the most are the *perfect sorting* scenarios, where a larger share of the waste is sent to material recycling, 45%. This leads to smaller amounts to both landfills and to energy recovery through incineration. The scenarios with central sorting also have a slightly larger share that becomes material recycled than the other scenarios, 35% and 34% compared to 31%.

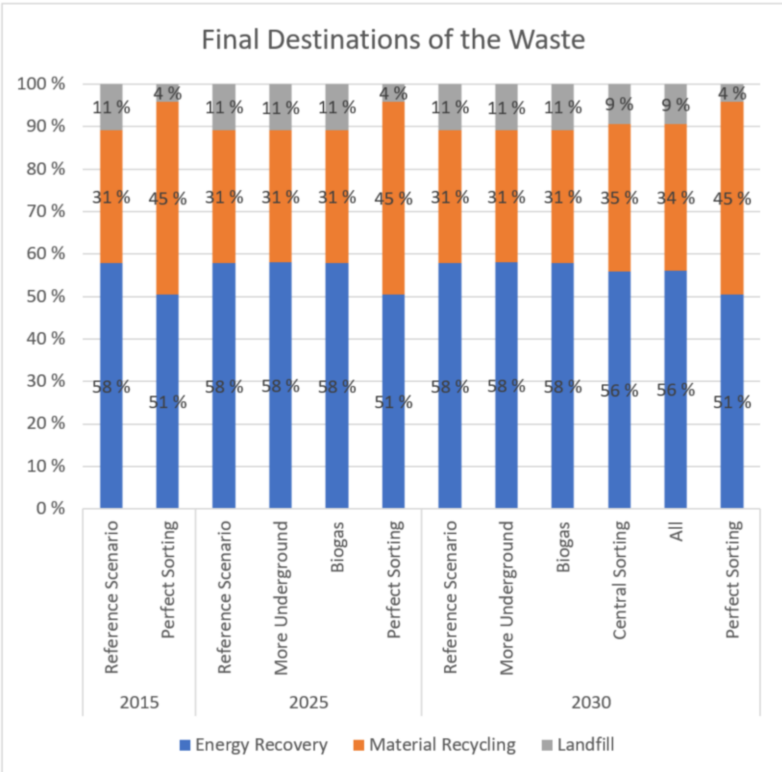


**Figure 5.7:** The final destination of the waste for the different scenarios over time.

Figure 5.8 shows where the waste is sent for treatment, in other words, what the waste is prepared for, which are the amounts that must be reported to the government. [EC, 2015b] [Fund, 2017] The continuous black line shows the proposed material recycling target for 2030 and the dashed line is the proposed target for 2025. It is important to note that these targets apply to the total amount of waste, not just household waste. This applies to the marked targets in the following figures as well.

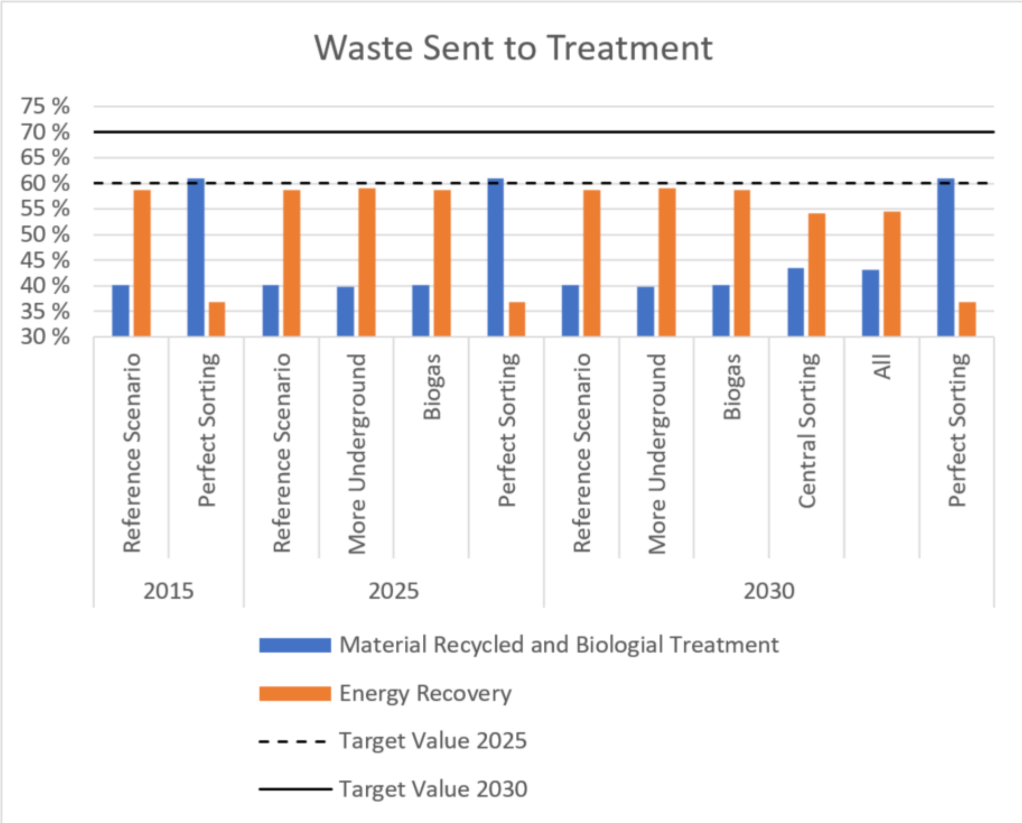


**Figure 5.8:** The rates of the waste sent to final treatment for the different scenarios over time.

The collection-, sorting-, and recycling efficiency for the glass fraction of the different scenarios over time are shown in figure 5.9. It is important to note that the proposed targets apply to all glass waste, not just the glass waste collected from households. In Norway, not all glass packaging ends up in the waste, some is also reused or material recycled through the bottle return system. Glass is still a fraction in the household waste with a quite high rate of material recycling, over 60% for all the scenarios. In the *perfect sorting* scenario the material recycling efficiency reaches 99%.

Figure 5.10 shows the collection-, sorting-, and recycling efficiency for the metal fraction of the different scenarios over time. The metal fraction reaches the proposed targets for material recycling in all the scenarios. The material recycling efficiency is 97% for all scenarios, apart from the *perfect sorting* scenarios where it is 100%. The sorting efficiency is clearly higher for the scenarios with a central sorting facility.

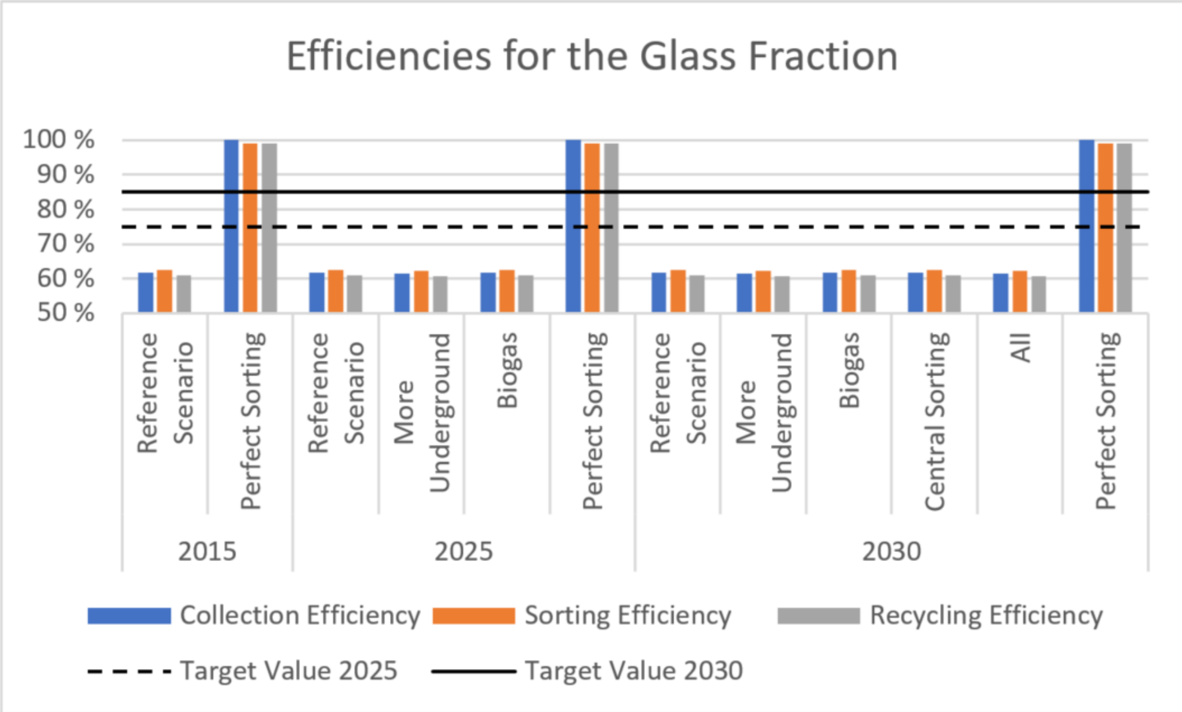


**Figure 5.9:** The collection-, sorting- and recycling efficiency for the glass fraction of the different scenarios over time.

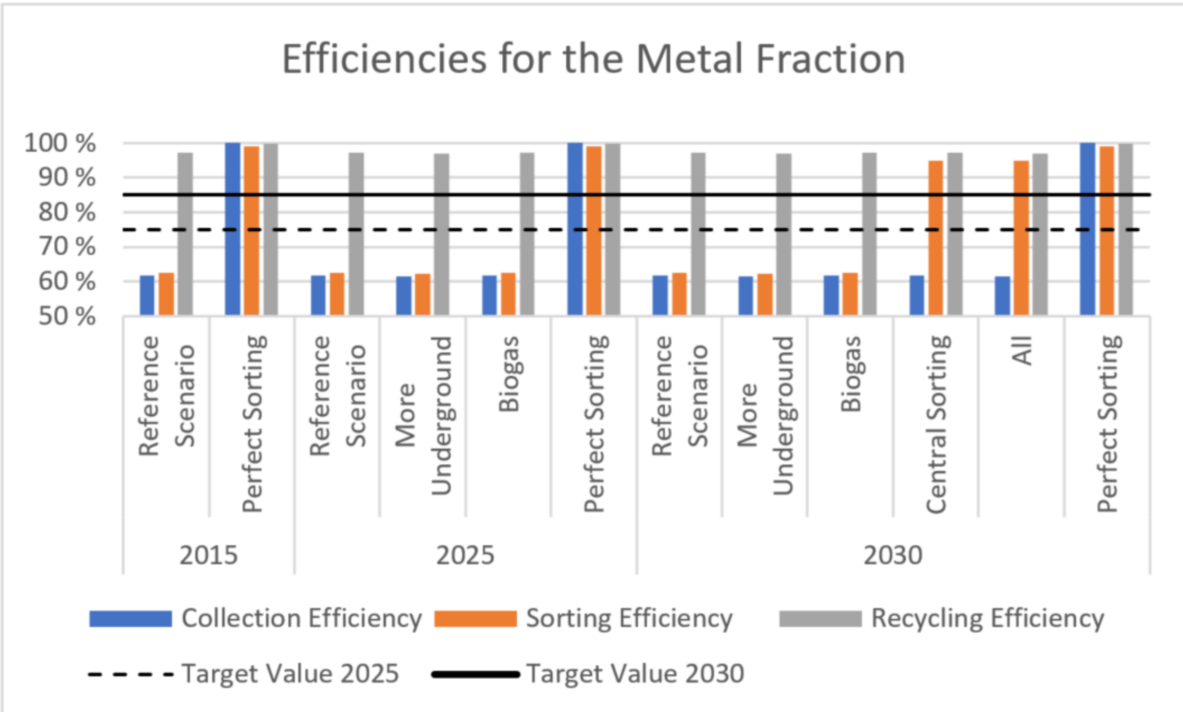


**Figure 5.10:** The collection-, sorting- and recycling efficiency for the metal fraction of the different scenarios over time.

Figure 5.11 shows the efficiencies for the organic waste fraction. There are no similar proposed targets for this waste fraction, as mentioned in chapter 2, and consequently there are no targets shown in this figure. Apart form the perfect sorting scenarios, the results for the different scenarios are almost completely the same, with a material recycling efficiency of 46%. It is important to note that all the organic waste sent to biological treatment is considered material recycled. This is in line with the reporting practice in the EU. The organic fraction have a general lower collection efficiency than the two previous fractions, which shows that more of the organic waste is sorted incorrectly in the households.

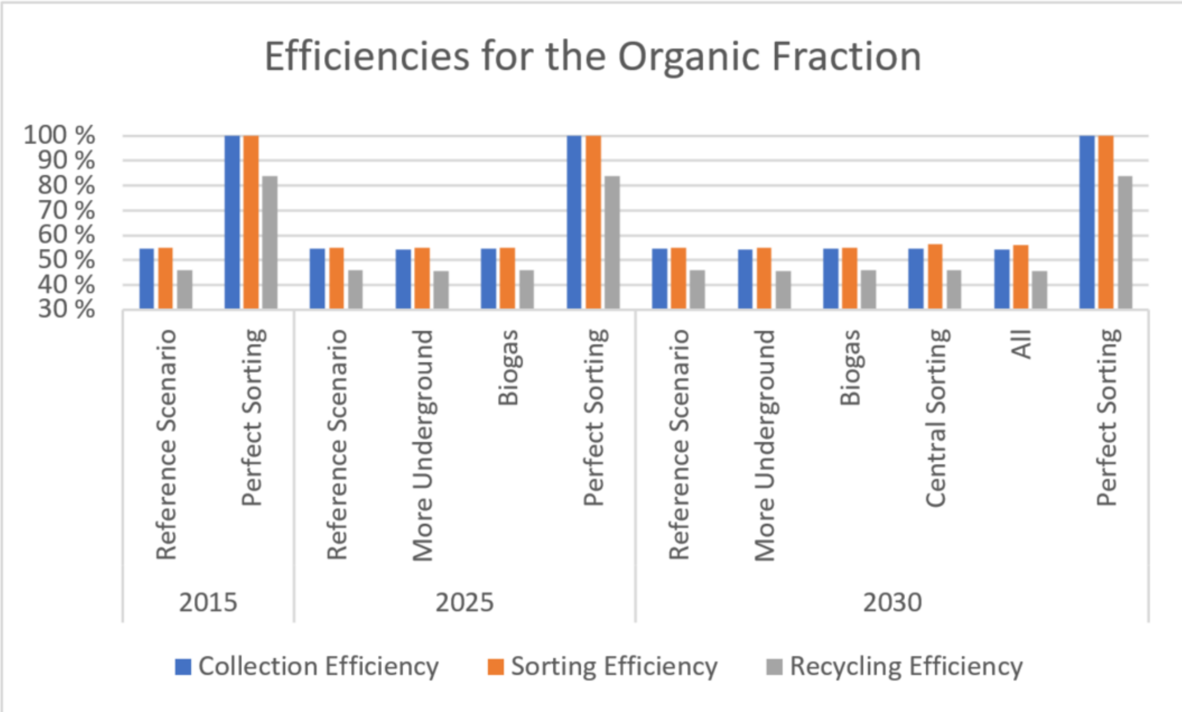


**Figure 5.11:** The collection-, sorting- and recycling efficiency for the organic fraction for the different scenarios over time.

There are proposed targets for a decrease in the growth rate of organic waste. The growth in organic waste is therefore shown in figure 5.12 as growth rate in percent per capita compared to the 2015 level. This shows that there is a growth of almost 30% for 2025 and around 45% for 2030. This was expected, as it was assumed a general growth in waste amounts per capita and no change in the composition of the household waste. Again, it is important to remember that household waste is just a share of the total waste amounts.

The collection efficiency for the mixed residual waste fraction, the rest fraction, is shown in figure 5.13. The sorting-, and material recycling efficiency do not apply to this fraction. The collection efficiency is in general very high, with 93% as the lowest for the scenarios where a larger share of the collection technology is underground. The other scenarios have a collection efficiency of 94%, apart from the *perfect sorting* scenarios which obviously have 100%. The collection efficiency shows that almost all the fractions belonging in the rest fraction are sorted correctly, but it does not show how much of the waste that incorrectly is sorted into the rest fraction. See figure 4.3 for an overview of the household sorting.

Figure 5.14 shows the collection-, sorting-, and recycling efficiency for the paper and cardboard fraction of the different scenarios over time. Paper and cardboard is the fraction

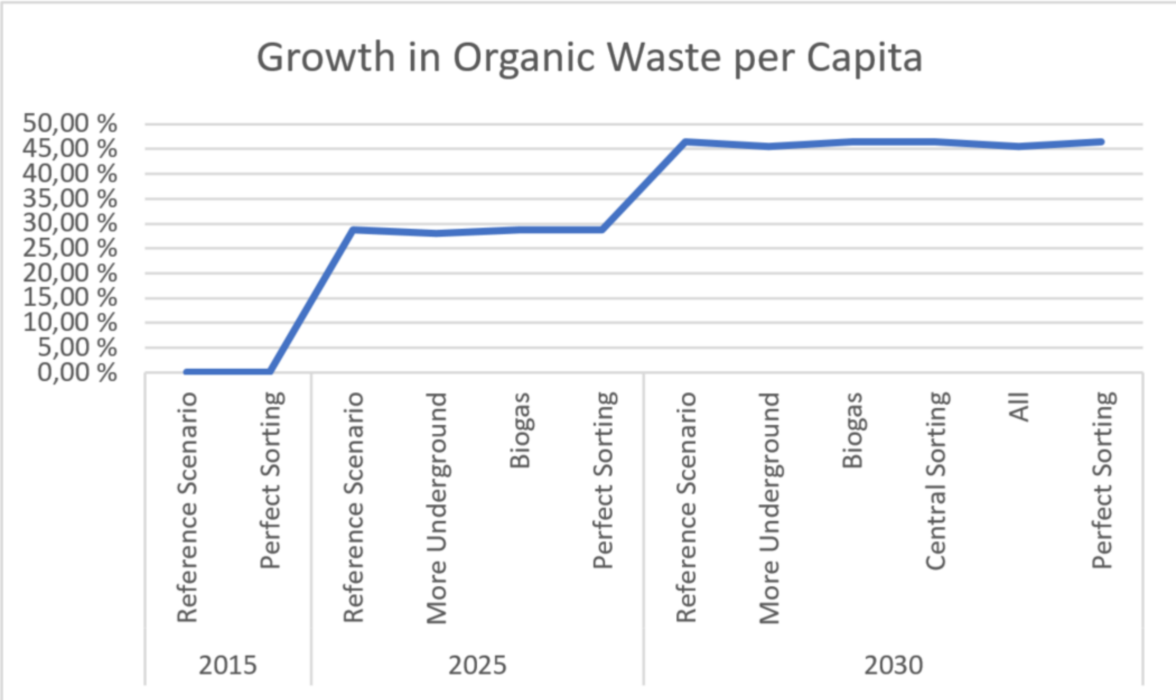


**Figure 5.12:** The growth in organic waste amounts for the different scenarios over time, compared to 2015.

with the highest efficiencies of all the fractions, apart from the material recycling efficiency of the metal fraction. The proposed target for 2025, the dashed black line, is reached for all the scenarios. The target for 2030 is reached for the *perfect sorting* scenarios.

The last figure in this section, figure 5.15, shows the collection-, sorting-, and recycling efficiency for the plastic waste fraction of the different scenarios over time. This fraction has the lowest efficiencies of all the fractions investigated. The collection efficiency, apart from the *perfect sorting* scenarios, is around 45%. The sorting efficiencies vary from 41% for most of the scenarios, to 53% for the scenarios with central sorting and 80% for the *perfect sorting* scenarios. The material recycling efficiency varies from 34% to 45% and 76%. It is clear that a central sorting facility has a positive impact on the material recycling rate of the plastic fraction.

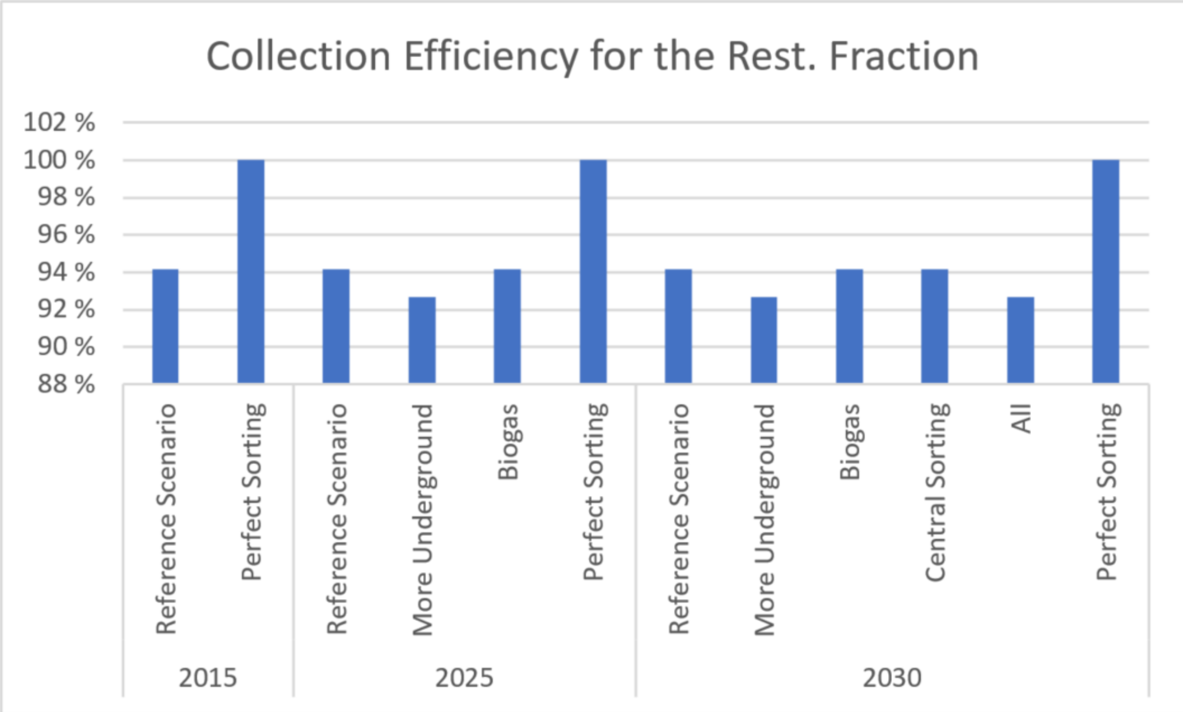


**Figure 5.13:** The collection efficiency for the rest. fraction for the different scenarios over time.

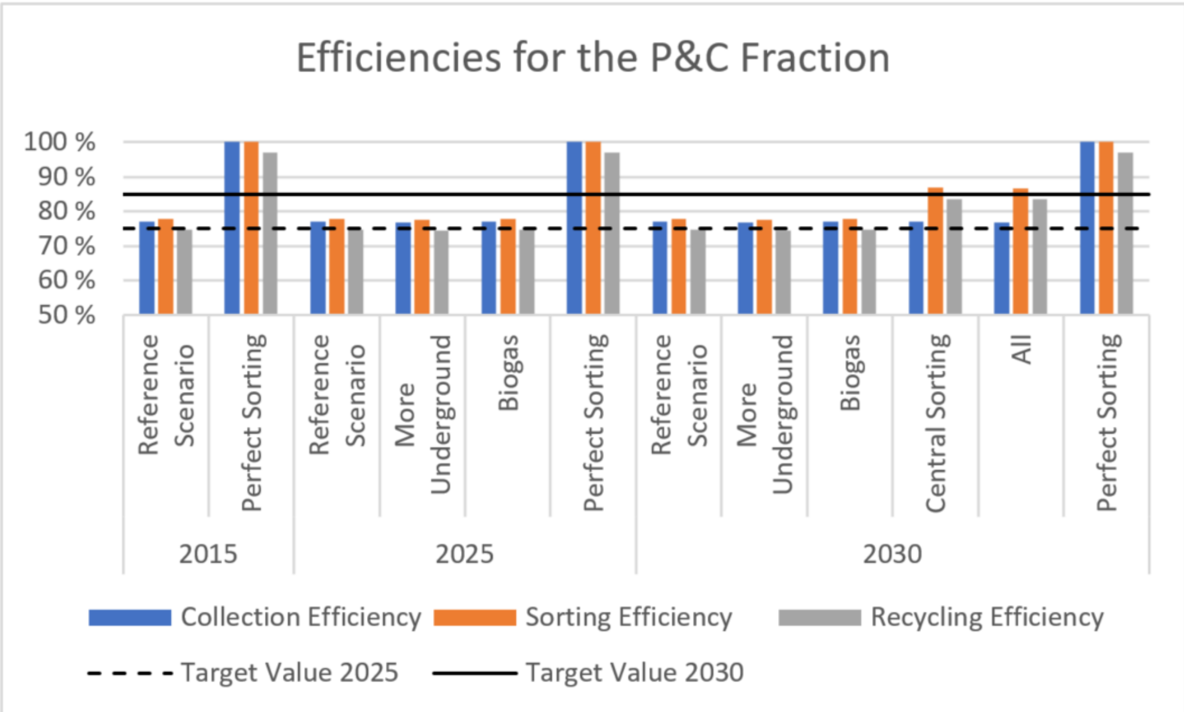


**Figure 5.14:** The collection-, sorting- and recycling efficiency for the paper and cardboard fraction of the different scenarios over time.

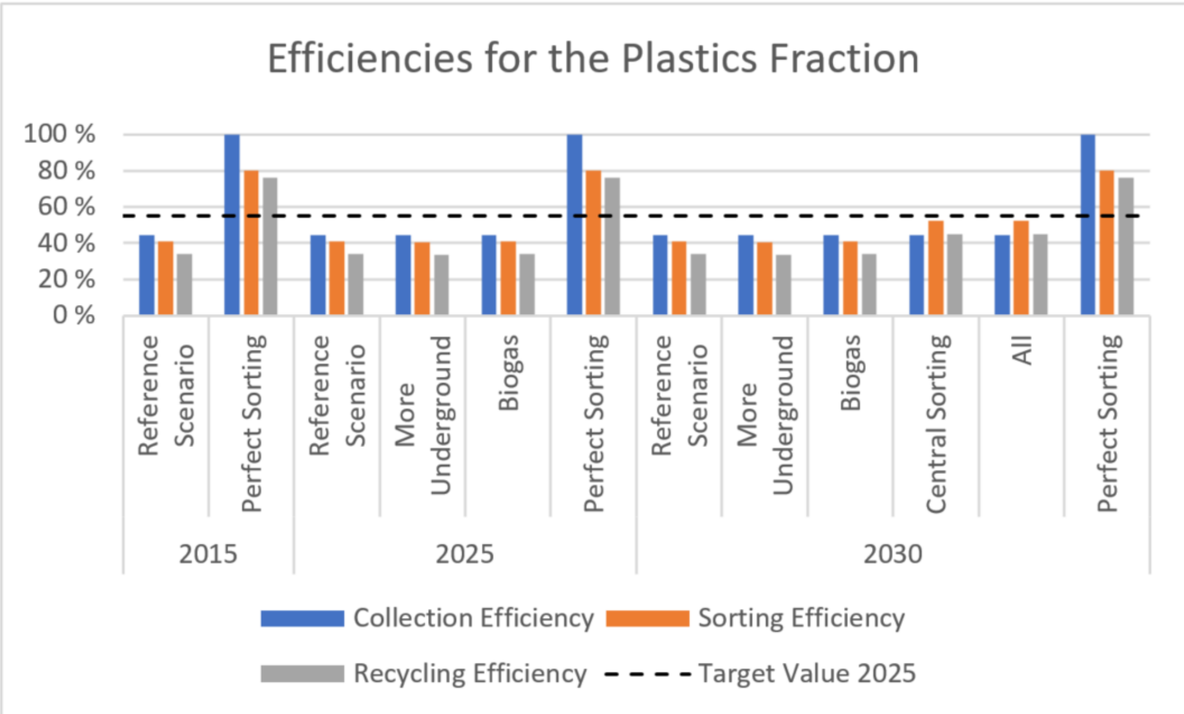


**Figure 5.15:** The collection-, sorting- and recycling efficiency for the plastics fraction of the different scenarios over time.

### 5.7.2 Energy

The total energy efficiency of the system for the different scenarios over time is shown in figure 5.16. It has been calculated in the model with equation 3.12. The energy efficiency varies from 13% for the *perfect sorting* scenarios, to 14% for the scenarios including a central sorting facility and 16% for the rest of the scenarios.

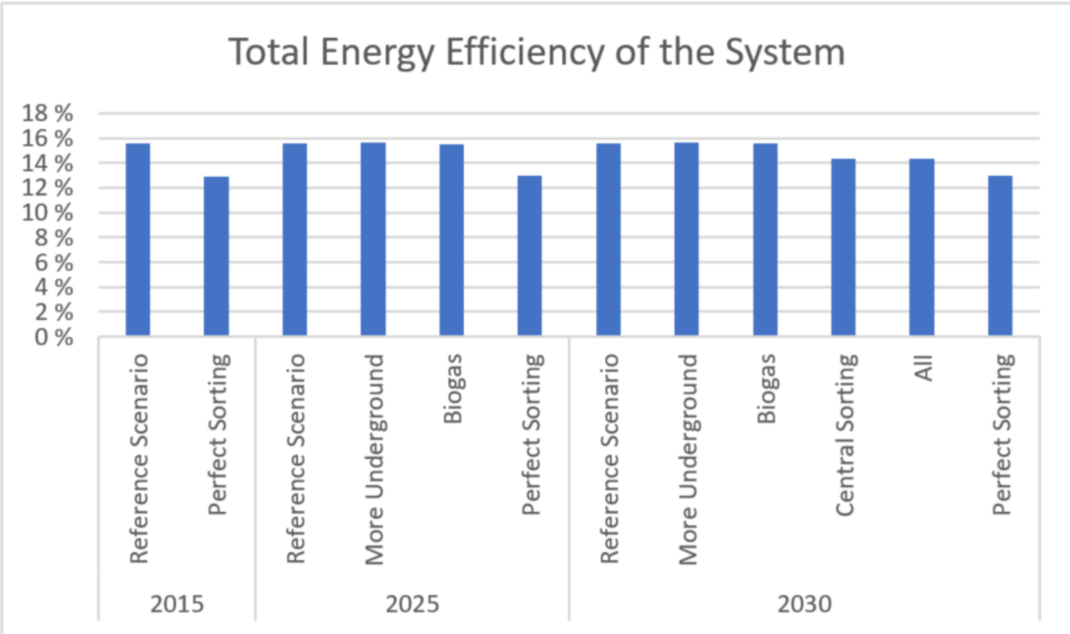


**Figure 5.16:** The total energy efficiency of the system for the different scenarios over time.

Figure 5.17 shows the total net energy flow of the system. It is negative for all of the scenarios, which means that there is more energy going into the system than produced energy going out of it. There is a clear increase from year to year. The scenarios with a higher degree of sorting also have a slightly more negative net energy flow than the rest of the scenarios.

The net energy flow of the system in kWh per kg generated waste is shown in figure 5.18. This figure further demonstrates the trends seen in figure 5.17. Here it becomes clear that the scenarios with the least amount of negative energy flow are the *reference scenarios*. The *more underground* and then the *biogas* scenarios follow closely. Here it also becomes clear that the net energy flow per kg generated waste is almost the same for each scenario over time.

Figure 5.19 shows the shares of energy flow into the system. The energy going into the system is divided between feedstock energy, the energy stored in the waste, the energy consumed by transport and the energy consumed by the different technical processes in the system, mainly the sorting and treatment processes. The distribution between the types of energy for the different scenarios are very similar. The feedstock energy is by far the largest contributor to the energy flow into the system, with 89% or 90% of the amount. Transport is the smallest contributor with between 4% and 5%.

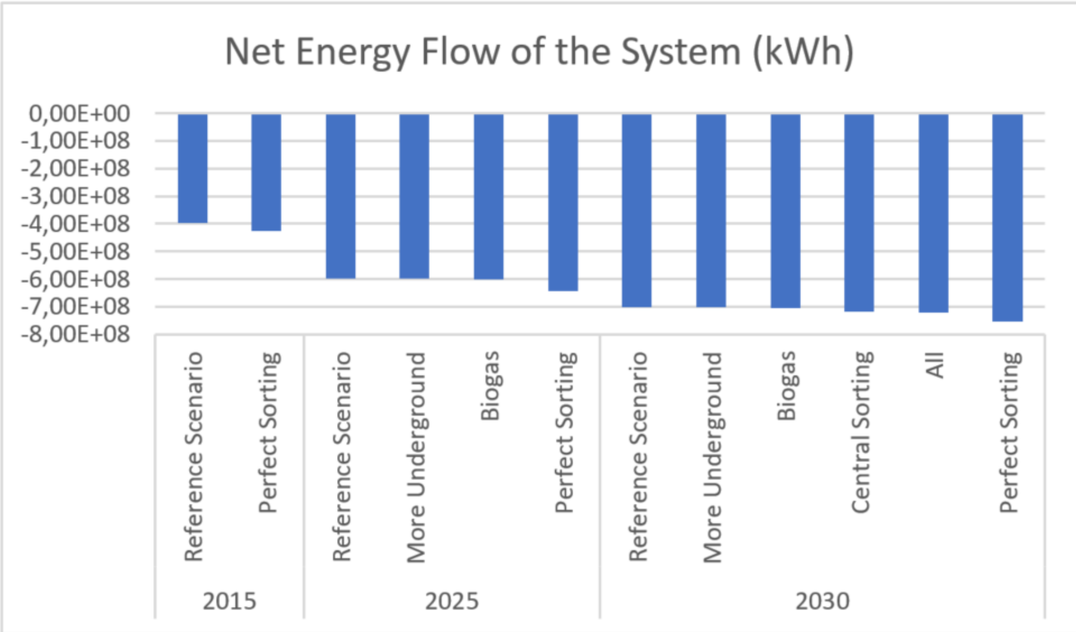


**Figure 5.17:** The net energy flow of the system in kWh for the different scenarios over time.

The total energy production in kWh for the different scenarios over time is shown in figure 5.20. The amount of energy produced increases from year to year, which was expected as the amounts of waste grows. The *perfect sorting* scenarios produces the least amount of energy. Heat from incineration is by far the largest contributor with around 68% of the total production for all the scenarios, except for the *perfect sorting* scenarios where it is around 58%. The share of electricity varies accordingly between 19% and 16%. The energy produced as biogas from the biological treatment of the organic waste varies between around 12% and 25%.

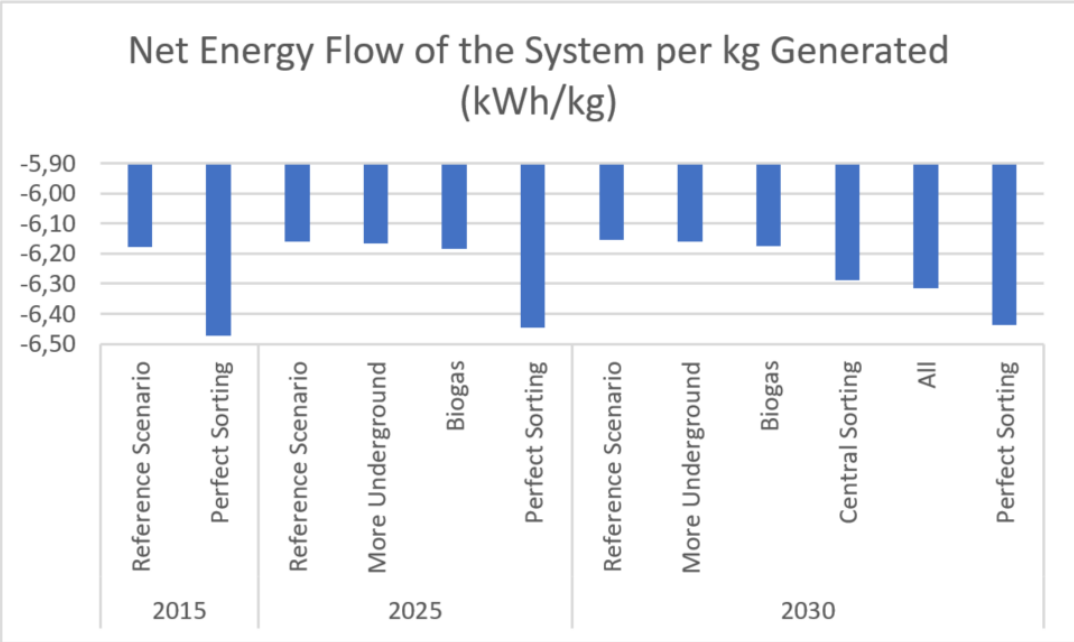


**Figure 5.18:** The net energy flow of the system in kWh per kg of generated waste for the different scenarios over time.

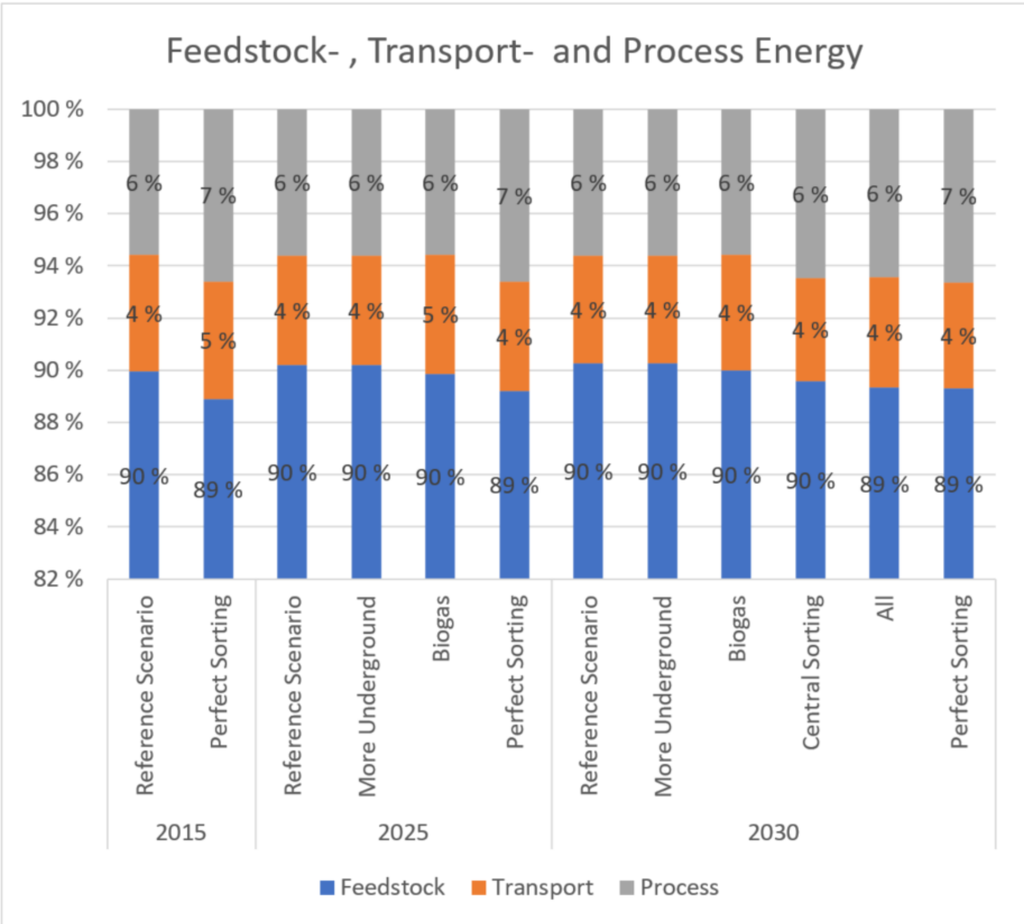


**Figure 5.19:** The energy flows into the system divided by feedstock-, transport- and process energy for the different scenarios over time.

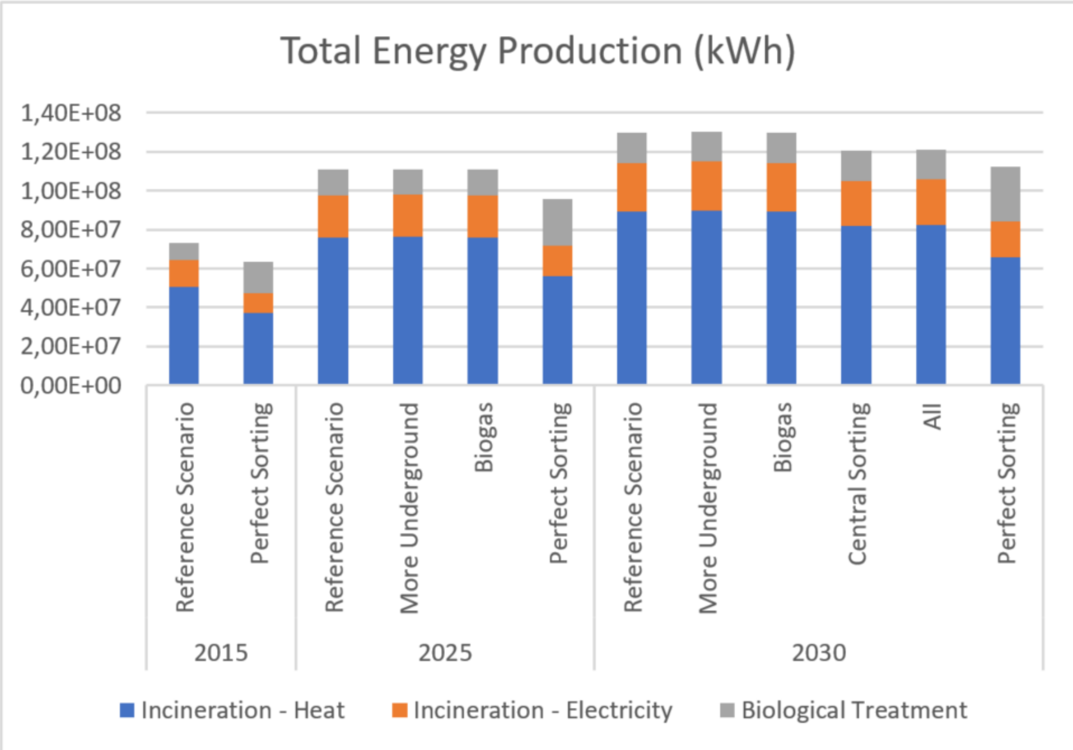


**Figure 5.20:** The total energy production of the system for the different scenarios over time.

### 5.7.3 Emissions

The total net emissions in kg CO2-equivalents of the waste management system for the different scenarios over time is shown in figure 5.21. The *perfect sorting* scenarios have negative net emissions, which means that the avoided emissions are greater than the emissions caused by the processes in the system. The *more underground* scenarios have the highest net emissions, followed by the *reference scenarios* and then the *biogas scenarios*. The *central sorting* scenarios have around half the emissions of the more underground scenario in the same year. The overall lowest positive net emissions belong to the *all scenarios* scenario.

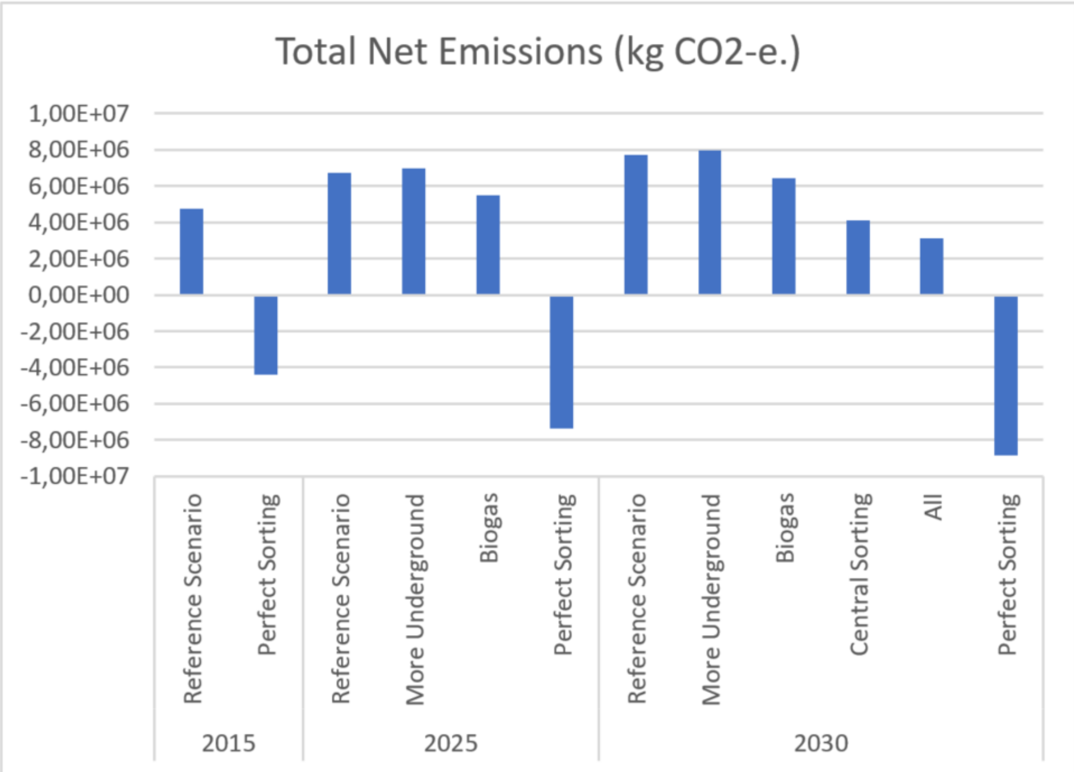


**Figure 5.21:** The total net emissions of the system in kg CO2-e. for the different scenarios over time.

Figure 5.22 shows the shares of emissions connected to the main process types in the system. The main process types are transportation, sorting, recycling and incineration. Incineration causes the largest share of the emissions, varying from 39% for the *perfect sorting* scenarios to around 50% to 55% for the other scenarios. For the *perfect sorting* scenarios, a larger share of the emissions are connected to the recycling processes. The variations in the share of transport emissions range from 12% for the *all scenarios* scenario to 17% in the *perfect sorting* scenario in 2015. The two scenarios with a central sorting facility have the highest share of sorting emissions of 1%, which is still very low.

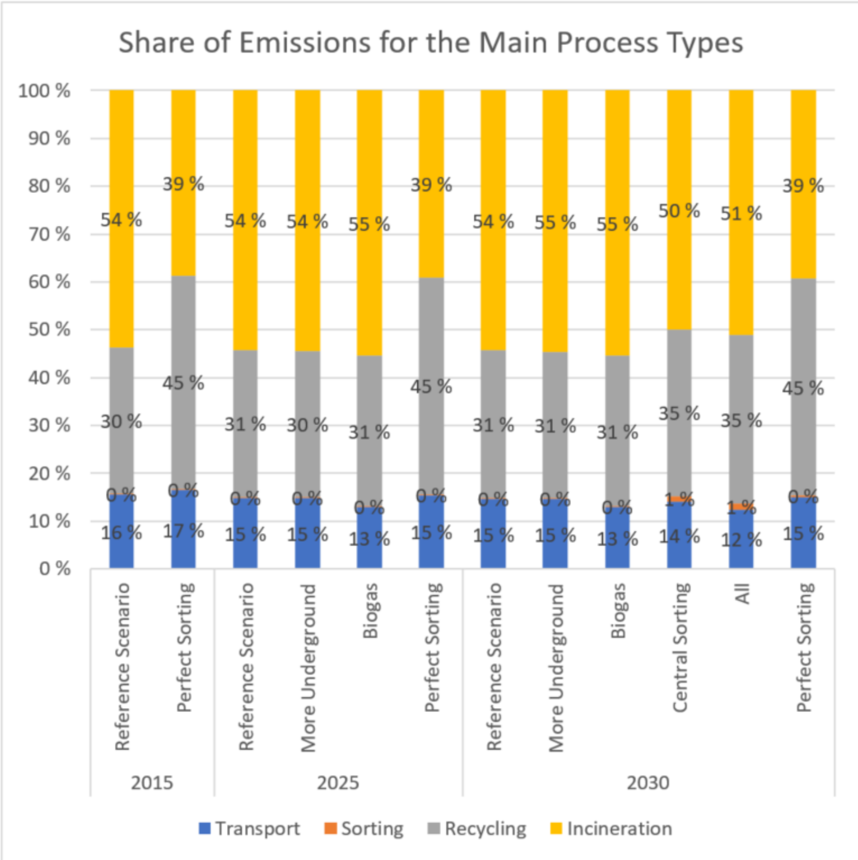


**Figure 5.22:** The share of emissions from the main types of processes in the system for the different scenarios over time.

The net climate impact in kg CO2-equivalents per inhabitant for the different scenarios over time is shown in figure 5.23. The impact of the different fractions are shown together and make up the total net impact per inhabitant for each scenario. The rest fraction is the only fraction which causes net emissions in all the scenarios. Glass have no net climate impact, apart from in the *perfect sorting* scenarios where the net impact is -1. A negative impact in this case, is positive for the environment. Metal, organic and paper and cardboard all have a net negative climate impact, which means that the avoided emissions are greater than the produced emissions. Plastic is the only fraction that changes from a positive climate impact to a negative for certain scenarios. The impact is negative in the perfect sorting scenarios. When added together, the net impact per inhabitant is negative for all scenarios.

Figure 5.24 shows the total net climate impact in kg CO2-e. per waste flow for the different scenarios over time. The total climate impact is positive for all the scenarios, unlike in figure 5.23 where the net climate impact per inhabitant is negative for all scenarios. The by far largest contributor to the climate impact is the rest waste flow. An interesting result is that the plastic waste flow has a negative impact for all scenarios apart from the scenarios with a central sorting facility. Figure 5.23 showed that plastics as a waste fraction, had a positive net climate impact per inhabitant for most of the scenarios. The largest contributor to a negative climate impact is the paper and cardboard flow followed

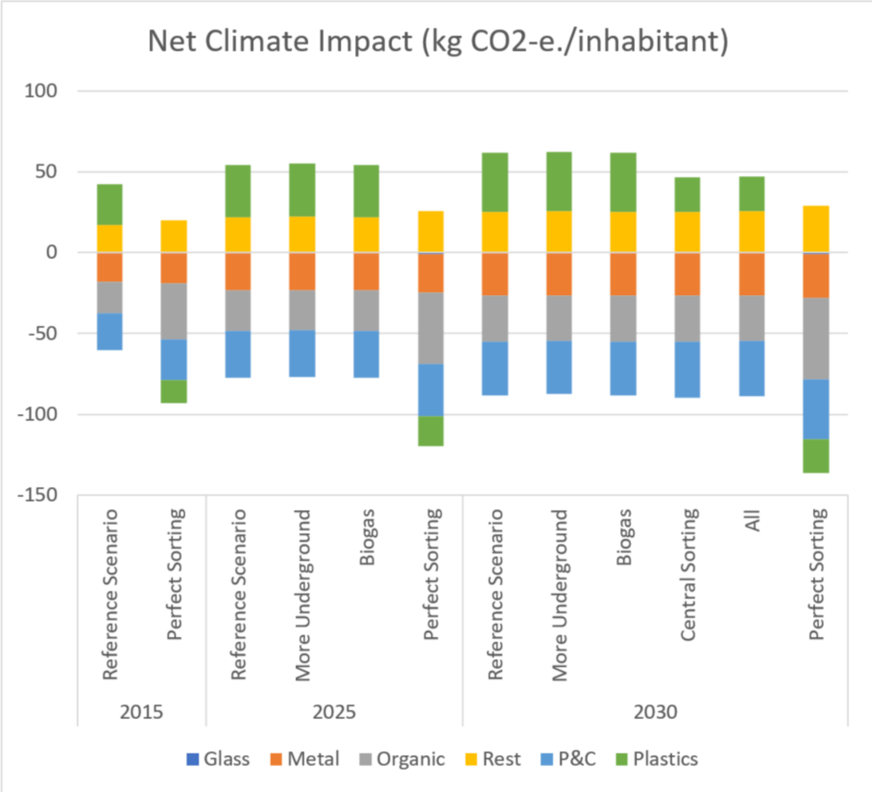


**Figure 5.23:** The net climate impact in, kg CO2-e., per inhabitant of the system for the different scenarios over time.

by glass and metal.

The total avoided emissions in kg CO2-equivalents per waste fraction is shown in figure 5.25. It is a clear trend of increasing amounts of emissions between the years, as expected with increased waste amounts. The *perfect sorting* scenarios have the highest amount of avoided emissions. The two scenarios with a central sorting facility have the second highest amounts of avoided emissions. Paper and cardboard is the fraction that contributes the most to avoided emissions, followed by the rest fraction.

Figure 5.26 shows the total transport emissions in kg CO2-equivalents for the different scenarios over time. The emissions are divided between transport from the households, to the collection parks, to the reloading stations and all further transport in the system, called downstream. The downstream transport is the largest share for all scenarios. An important result is that there are no transport emissions from the households for the scenarios that include biogas. This is because emissions from biogenic sources are set to 0. This also affects parts of the transport to the reloading stations, as the same vehicles are used from the households and to the reloading station. Another interesting result is the amount of emissions caused by transport to the collection parks. It is very large considered the fact that the amount of waste transported is much smaller than what is collected at the households.

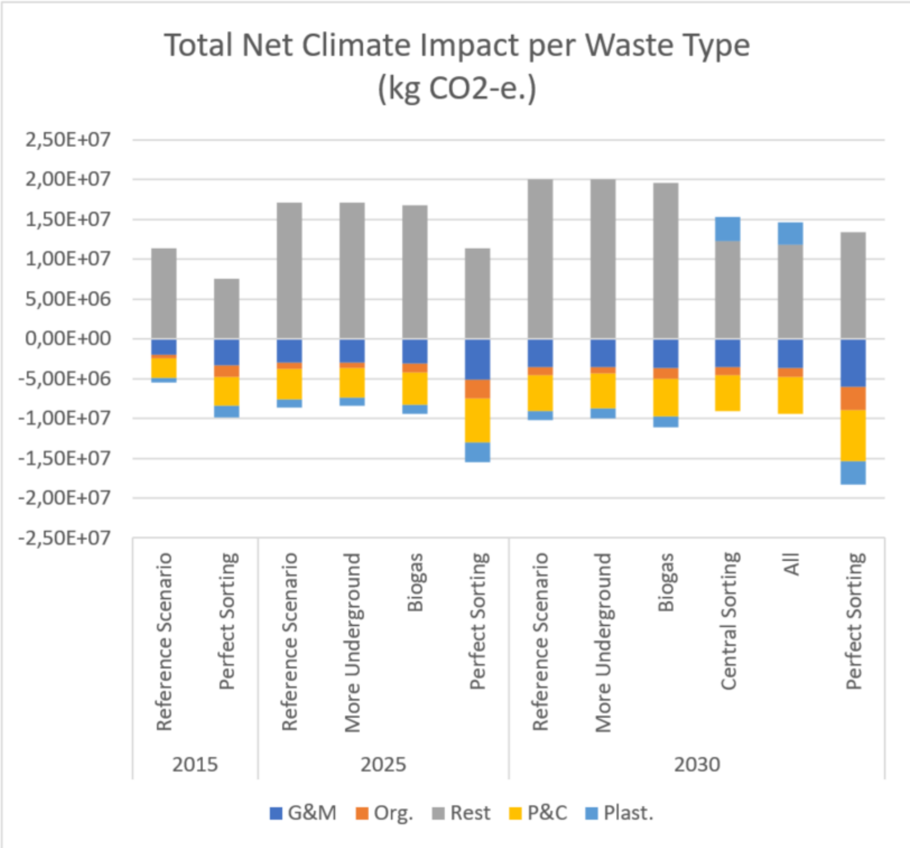


**Figure 5.24:** The total net climate impact, in kg CO2-e., per waste flow of the system for the different scenarios over time.

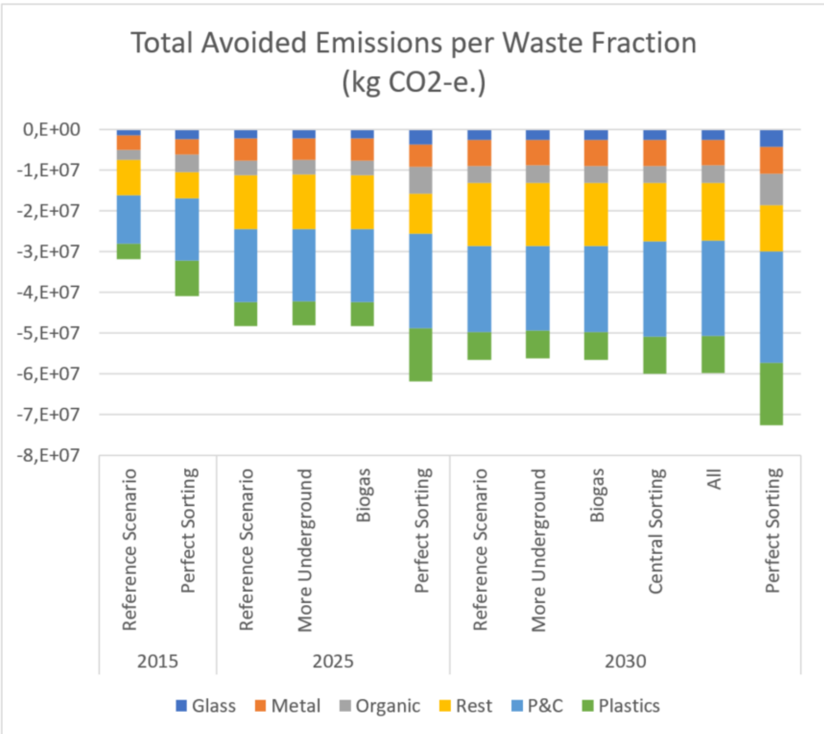


**Figure 5.25:** The total avoided emissions, in kg CO2-e., per waste fraction of the system for the different scenarios over time.

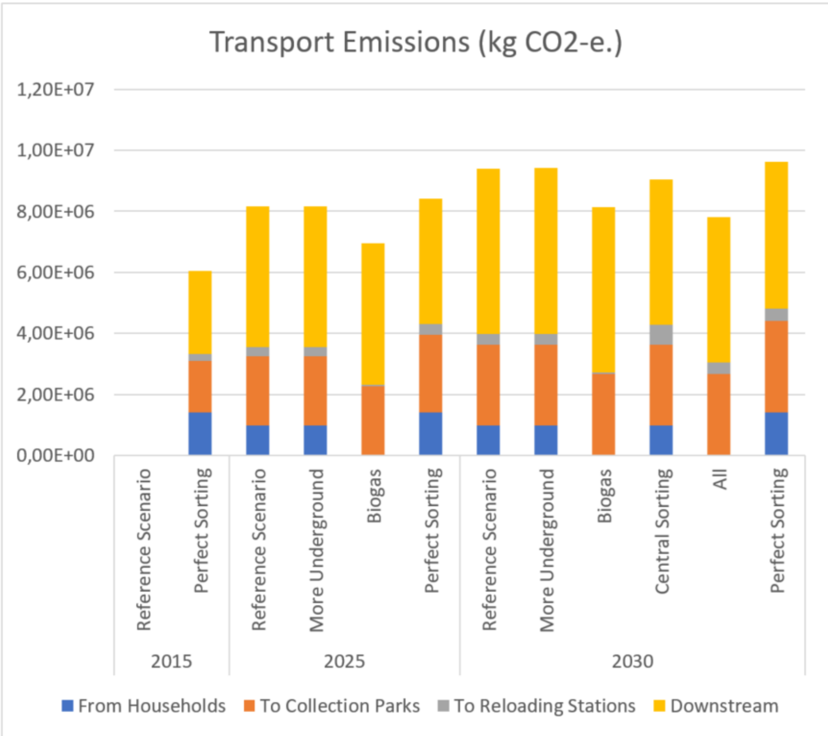


**Figure 5.26:** The total transport emissions, in kg CO2-e., of the system for the different scenarios over time.

## 5.8 Sensitivity Analysis

A sensitivity analysis has been conducted to investigate the impact on the system when different parameters are changed. The sensitivity analysis is not as comprehensive as preferred, as this function in the model did not work properly. The investigated parameters are the degree of sorting in the central sorting facility, the degree of sorting in pre-treatment of material recycling, the effectiveness of material recycling as well as the emission factors for avoided emissions for the different waste fractions and for different electricity mixes.

### 5.8.1 Sorting and Material Recycling

Sorting has been recognized as a critical factor for the material recycling rate of the system. The impacts of changes in these factors are therefore investigated through a sensitivity analysis.

**Central sorting.** The amount of plastic sorted out from the rest waste in the central sorting facility was improved by 1%. This lead to an increase in the material recycling of plastic of 0,2%. When the improvement was of 10%, the change in material recycling rate was 2,4%. To increase the amount of metals sorted out by 1% led to no change in the material recycling rate and and neither did an increase of 10%. Improving the sorting of paper and cardboard by 1% led to an increased material recycling rate for paper and cardboard of 0,09% and an improvement of 10% led to an increase of 0,88%. The overall energy efficiencies of the system were affected negatively with about 0,01% for all the situations.

**Sorting before the treatment facility.** The sorting of glass in the glass and metal flow before the the treatment facility, process 6, was made less effective by 1%. This resulted in a lower material recycling rate for glass of 0,62%, but no noticeable change in the overall energy efficiency of the system. A change of 10% caused a 6,1% lower material recycling rate for glass, but still no noticeable change in the energy efficiency. The same was done for the sorting of metal in the glass and metal waste flow in process 6. A change of 1% led to no noticeable changes for the material recycling efficiency or the overall energy efficiency. A change of 10% caused a decrease in the material recycling rate of 0,005%, but no change in the overall energy efficiency.

**Material Recycling.** The material recycling process for paper and cardboard was made less effective by 1%, which means that 1% less paper and cardboard was material recycled and sent to incineration in stead. This led to a decrease in the material recycling rate of paper and cardboard of 0,02% and an increase in the overall system energy efficiency of 0,001%. A change of 10% in the material recycling process resulted in a decrease of 0,23% for the material recycling efficiency and an increase of 0,01% in the overall energy efficiency. The same was done for the material recycling process of plastic. A less effective material recycling process by 1% caused a decrease in the material recycling efficiency of plastic of 0,01%. A change of 10% resulted in a decrease of 0,1% but close to no change in the overall energy efficiency.

### 5.8.2 CO2 Emission Factors

The chosen CO2 emission factors have a great impact on the GHG emissions of the system and consequently the environmental performance. Different CO2 emission factors are therefore investigated more closely in a sensitivity analysis. The consequences of changing some of these factors are presented to identify their importance and impact on the system performance.

**Electricity mix.** Changing from the Nordel electricity mix with an emission factor of ca 0,190 kg CO2-e./kWh to the Norwegian mix with an emission factor of ca 0,044 kg CO2-e./kWh reduces the emissions of the process energy consumption of the sorting processes by 23%. These processes only require electricity and as the energy consumption of the sorting processes only makes up 0,045% of the total energy demand of the system, the overall system performance remains unchanged for the *reference scenario* in 2015. The emissions of the recycling and incineration processes are already given from Ecoinvent, and are therefore not subject to changes within this sensitivity analysis.

**Avoided emissions.** Improving the CO2 factor for avoided emissions connected to the plastics fraction by changing the factor with 10% from -1,783 kg CO2-e./kg to -1,961 kg CO2-e./kg leads to an increasing amount of avoided emissions for the plastics fraction. The result is an improvement of 65% for the total net climate impact of the plastic waste flow. The net total climate impact in kg CO2-equivalents changes from -5,95E+05 to -9,82E+05 in the *reference scenario* in 2015. The net impact in kg CO2-equivalents per waste fraction and inhabitant changes from 25 to 23 for the plastic waste flow, a change of 9%. The same change was applied to the other fractions as well. The glass and metal waste flow had an improvement in the net total climate impact of 19%, rest 6% and 48% for the paper and cardboard waste flow. There was no change in net total impact for the organic waste flow as a result of an increased avoided emissions factor. The improvement of the factors for glass and metal slightly improved the net total climate impact of the other waste flows as well. The plastics waste flow had the largest improvement of all the waste flows, when the desirable fraction of the specific waste flow was changed.

# Chapter 6

# Discussion

## 6.1 Main Findings

The objective of the thesis is to model and analyse the system efficiency of the urban waste management system of RfD. This section evaluates the research questions, as introduced in chapter 1, using the results as presented and aggregated within the previous chapter. First of all, it can be concluded that the data as generated by the model suits the actual conditions and data provided by RfD. The *reference scenarios* represent the actual situation in 2015 and the "business as usual" outcomes for 2025 and 2030. There have been taken no measures to improve the environmental performance in these scenarios, which is necessary to be able to evaluate eventual impacts of measures taken in the other scenarios.

The *more underground* scenario represents a change in collection technologies, with more underground solutions, more often seen in urban and densely populated areas. The *biogas* scenario represents a measure taken to reduce the GHG emissions of the collection transport in the system. The vehicles that collect the waste from the households are fuelled by biogas instead of diesel. This is a scenario requested by RfD as they are substituting their collection vehicle fleet to biogas-only in 2017. The *central sorting* scenario looks into the impact of including a central sorting facility in the system. This is a measure that aims to improve the material recycling rate of plastic waste especially. The *all scenarios* scenario combines the measures of the *more underground*, the *biogas* and the *central sorting* scenario. The last scenario investigated, the *perfect sorting* scenario investigates the impact of perfect sorting in the household, and is the most unlikely and highly theoretical of all the scenarios. The results are still important to determine the impact of sorting as a critical factor for the environmental performance of the waste management system, and can be seen as a sensitivity analysis of sorting as a critical parameter.

### 6.1.1 Material Recycling

Material recycling is a very important and critical indicator of the transition towards circular economy. A high material recycling rate is desirable from a material resource point of view, but an increase in material recycling also effects the energy efficiency and the GHG emissions of the system. The total environmental performance of the system is dependant on all of these indicators and it is therefore important to find the measures that maximise the environmental performance, which might not be the measures that maximise the material recycling alone. The first research question is how measures motivated by circular economy influence the material recycling rate of the different materials in the system. The results presented in chapter 5.7.1 are therefore discussed in the following paragraphs.

As mentioned in chapter 5.7.1, it is important to note that the targets marked in the figures are proposed targets that are not legally binding for Norway and RfD, and that these targets include all kinds of waste, not just the chosen waste fractions in the household waste. Household waste is in general considered difficult to material recycle, as it is very heterogeneous compared to waste from most other sources. The targets are meant to motivate and to highlight areas of improvement, they do not say anything about RfD's total performance.

As seen in figure 5.7 the highest share of material recycling was achieved by the *perfect sorting* scenarios. The more correctly sorted the waste is, the more ends up in the right final treatment. For many of the waste flows, there is no additional sorting of all the waste fractions after the source, the households. The desirable fraction within each waste flow is often sorted out, but the rest of the fractions in that waste flow is then mostly sent to incineration. This means that any paper and cardboard in the plastic packaging waste type is not material recycled, but incinerated as there is no further sorting of paper and cardboard. Metal is an exception, as the bottom ash treatment, process 11, sorts out metal that can be material recycled. This is why the material recycling efficiency of the metal fraction is considerably higher than the sorting efficiency for all the scenarios. In general the material recycling efficiency is the lowest of the three efficiencies.

Organic waste and plastics are the fractions with the lowest efficiencies, especially for material recycling. These are both fractions where large amounts of the generated waste ends up in rest waste, instead of in the correct waste bin. This leads to less organic waste and plastic waste reaching the desirable treatment facility. These two fractions have great potential for improvement and should therefore be targeted when implementing circular economy measures in the system.

The central sorting facility adds a sorting of different fractions for the rest and plastic waste flows, then assumed to be collected together as one common waste type. This scenario represents a measure taken to improve the material recycling rate of the plastics fraction. The implementation of a central sorting facility improved the material recycling efficiency of paper and cardboard, and plastics. It is important to note that the sorting of plastic in the central sorting facility is highly dependant on the amount of organic waste in the facility. This scenario is based on data from the central sorting facility of RoAF, but as RfD most likely will continue the separate bin collection for organic waste, there will be a lower amount of organic waste in the facility. This results in less contaminated plastic waste and therefore a higher share of plastic sent to material recycling. This increase was assumed to be 14%, which might be an understatement, but there is still a lot of organic waste collected with the rest waste. Another important aspect is that the central sorting facility is capable of sorting more kinds of plastic that what is done today, but it is not profitable as the market price for secondary plastic material is not high enough or there are no buyers of that kind of plastic. The Ministry of Climate and Environment recognises this as an inhibitory factor and challenge to the utilization of the resources found in waste in the white paper of June 2017 [KLD, 2017].

The change in the degree of sorting for the *reference scenario* and the *more underground* scenario is very small and therefore does not impose a remarkable impact for the future prognoses for 2025 and 2030. The degree of sorting is slightly worse for the underground collection containers. This has several possible explanations. One point is that the underground solutions have far more users than the smaller containers. The small containers are usually only used by one single household and its members. The underground collection technologies often cover whole apartment buildings or neighborhoods. This also means that there is a higher chance of unintended users, people that pass by the containers, as they are often placed in public places or on the side of the road. People probably feel more responsible for the waste and the collection containers when their household is the only user. The consumers, or users, are difficult to influence, but they are still a very important variable in the system.

Underground solutions have other benefits that do not affect this system, but still make them attractive to the users and the waste management company. Collection containers that cover more households, might mean a shorter transportation distance for the collection vehicles, but that was not modelled. Other important factors for the users and the company are factors like noise, smell, hygiene, the way the containers look and so on. These factors do not pose an impact to the performance indicators in the model but are important for the overall performance of the system of RfD, and are therefore mentioned and discussed here.

The measures taken in the *more underground* and the *biogas* scenario do not influence the material recycling efficiency appreciably. The *perfect sorting* scenarios achieve the highest material recycling rates for all fractions, followed by the *central sorting* and the *all scenarios* scenarios. These results prove that sorting is a critical factor when it comes to material recycling rates.

### 6.1.2 Energy

The second research question emphasises on how measures for increased material recycling affect the energy consumption and GHG emissions of the system. The corresponding results regarding energy consumption will now be discussed within the current section, the results regarding emissions within the subsequent section. Discussing the results in the context of this second research question will also lead to the relevant findings and results required to answer the third research question, as clarified at the end of this section 6.1.

The overall energy efficiency of the system does not vary much across the different scenarios, but it is lower for the scenarios with a higher degree of material recycling. This is a consequence of a higher net energy flow in to the system, see figure 5.17 and 5.18. Material recycling and energy efficiency are closely connected, as increased material recycling means more energy consumed in sorting and material recycling processes, as well as less energy recovered through incineration. This is shown in figure 5.20. Material recycling can in some cases be more energy efficient than incineration, especially where material production from virgin material is very energy demanding, as it is with the production of aluminium.

The energy efficiency is also dependant on the technology used in the energy recovery processes. Many waste management systems do not have anaerobic biological treatment that produces biomethane, but composting in stead. The incineration process is also affected by the chosen technology. There exists a number of different furnace technologies with different qualities that affect the amount of energy recovered. The composition of the waste greatly affects the calorific value of the waste and therefore the temperatures reached and the energy recovered. A higher calorific value means higher temperature and more energy recovered, but many older furnaces are only built for certain maximum temperatures. When the composition of the household waste changes, with more plastics for instance, the calorific value of the waste is too high. Therefore it is often necessary to mix in fractions with lower calorific values, like organic waste, which preferably not should be burned because of a low energy recovery rate when incinerated. The technology is continuously improved, but the incineration of waste is a fairly mature practice and there are many old furnaces still in use.

The energy demand of the different processes is based on average numbers from the Ecoinvent database. It was very difficult to obtain specific data for the different treatment facilities, for several reasons. Many facilities have not responded when contacted or they do not have records of the requested data, or the data necessary to calculate the specific energy consumption per weight and waste fraction. In addition to this, many of the waste flows are sent to several different treatment facilities. The organic waste is sent to different biological treatment facilities and the rest waste is sent to many different incineration plants in both Norway and Sweden, consequently the data would have to average even with facility specific data. This means that the energy results are not completely accurate, but they should still give an adequate insight in relevant areas with potential for improvement as well as the relationship between important performance indicators.

The consumed transport energy was calculated with the equations as presented in chapter 3.4.2. The necessary factors can be found in the transportation section in appendix A. It was assumed that all vehicles were fuelled by either diesel or biomethane. This simplification is adequate for the commercial transportation, but is somewhat misleading for the transportation by personal vehicles. As equation 3.6 shows, the energy consumption relative to the waste transported depends on the weight of the waste, the transport distance, the collection frequency and the energy content of the fuel. This means that the relative energy intensity of the vehicle is lower the greater the amount of transported waste is. As a result the personal vehicles have on average a relative energy intensity of more than 300 times the energy intensity of the commercial collection vehicles. This explains the very high energy demand of the transport from the households to the collection parks.

The chosen measure taken to improve the material recycling rate of the system seems to lower the energy efficiency, as proven in the scenarios where the sorting and therefore the material recycling efficiency is improved. However, the decrease is not very large.

### 6.1.3 Emissions

The emissions are not only dependant on the energy efficiency, but also on the electricity mix chosen and the type of energy substituted by energy recovery of waste. The emissions are highly dependant on the CO2-factors used to calculate emissions based on energy consumption as well as whether emissions from certain energy sources should be counted or not.

**Electricity mix.** The waste management system has been modelled with the Nordel electricity mix, as this is common practice for LCAs in Norway and it was also requested by the supervisor. The Nordic electricity mix has 23% higher emissions in kg CO2-equivalents per kWh than the Norwegian electricity mix. The Norwegian electricity production is mainly based on water power and is therefore "cleaner" than the Nordic mix. The sensitivity analysis investigated the impact of changing from the Nordic mix to the Norwegian mix in the reference scenario in 2015 and found that it had no or very little impact on the overall system performance. However, it was only the process energy consumed by process 2,4,6 and 11 that were affected by the change in electricity mix, as the emissions for process 7,8,9 and 12 were given through Ecoinvent and could not as easily be investigated in the sensitivity analysis. As the energy consumption of the investigated processes make up only 0,045% of the system's energy consumption, it was expected that this would have very little impact on the total system performance.

**CO2 emission factors.** The chosen CO2 emission factors have a great impact on the climate impact and consequently the environmental performance of the system. The emission factors used in the modelling were mostly collected from the Ecoinvent database and from a research report by Østfoldforskning and are considered credible. The sensitivity analysis showed that the chosen emission factors have a great impact on the net climate impact of the waste fraction in question. This was especially apparent for the waste fractions with high CO2 factors, like plastics and paper and cardboard. Metal have the highest CO2 emissions factor, but the effect on the net climate impact of the glass and metal waste flow, was a lot smaller than for plastic and paper and cardboard. This is connected to the fact that glass makes up 2/3 of the glass and metal waste and that avoided emissions accounts for a relatively larger share of the emissions for this particular waste flow. What this sensitivity analysis shows, regardless of waste fractions and flows, is that the choice of CO2 emissions factors have a huge impact on the calculated climate impact of the system. A strategically choice of factors can affect the outcome of the modeling and thus favor certain measures over others. This underlines the importance of commonly acknowledged and standardised emission factors and frameworks to calculate and report on environmental performance, not only for waste management systems, but in general.

In line with literature and common LCA practice, CO2 emissions from biogenic energy sources have not been counted in the modelling, as they are considered neutral as the carbon emitted equals the carbon taken up in the organism during its lifetime. Consequently there are no GHG emissions connected to the transportation vehicles fuelled by biogas. Some argue that this should also be the practice for waste fractions like paper and cardboard and organic waste, as these are based on biogenic material. This is not common practice and have not been done in this thesis.

**Critical processes.** As seen in figure 5.22, incineration produces more than half of the GHG emissions in the system for all scenarios, except for the *perfect sorting* scenarios where the share is close to 40%. This marks incineration as a process with great potential for improvement that needs to be targeted. Reduced amounts to incineration will of course reduce the emissions as more than half of the generated waste is sent to energy recovery by incineration for all scenarios. A reduction of plastic in the burned residual waste will also reduce the emissions, as this is a fraction with high a CO2 emission factor. However, there will still be waste fractions that are not suited for material recycling and incineration with energy recovery is more environmental friendly than landfilling. A solution for the future can therefore be to reduce the emissions by capturing and storing the GHGs emitted through incineration.

Material recycling is of course also a critical process, as it requires energy, but also because it avoids the production of virgin material, which in many cases is more energy demanding than recycling. This is especially evident for metals. Recycling of aluminium consumes only around 5% of the energy used in production from virgin material. [Christensen, 2011] The WRAP study argued that a lower-carbon energy mix, increases the environmental friendliness of material recycling over incineration. [Michaud, 2010] Another important aspect of material recycling is to keep limited resources in a loop within in the society. The material technology of the glass, metal and paper and cardboard waste fractions are fairly mature and therefore not likely to change much in the future. The material recycling technology for organic and plastic waste is still developing and has potential for improvements which most likely will increase the material recycling rate and lower the climate impact of these fractions. Consequently, these technologies should also be targeted.

The transport emissions in the system are based on the energy consumption of the transportation. Consequently, the emissions from the personal vehicles are comparably greater than the emissions from the other collection transport. For simplification, the personal vehicles were assumed to be fuelled by diesel, which is not a good representation of the actual situation. Most cars in Norway are fuelled by regular petrol fuel and an increasing amount are electric cars. This means that the emissions in reality are probably lower than what these results show. It is still an important area to highlight as the emissions from this transportation are considerable compared to the rest of the transport in the system, as figures 5.2 and 5.3 show.

The emissions from personal vehicles are inside the chosen system boundaries, but should not be counted when adding up the emissions resulting from RfD's activities as these emissions are outside of the control of the company. The company can still take measures to help to reduce these emissions. Relevant measures can be to shorten the transportation distance by increasing the number of collection parks or offer additional collection services like waste “taxis” that collect the waste at peoples households on request. Another important aspect to keep in mind about the emissions of the transport of waste to the collection parks, is that the waste fractions collected at the households are not directly comparable to the fractions collected at the collection parks, although that has been the assumption in this modelling. For simplicity the characteristics of the chosen waste fractions have been assumed to be the same, but the truth is that mixed residual waste in collection parks often is very different from the same fraction collected directly from the households. The fraction received in collection parks often consists of more bulky or complex waste that is not as easily transported, sorted and recycled.

**Critical fractions.** Figure 5.23 and figure 5.24 show that plastic waste has great potential for improvement when it comes to climate impact. The net climate impact per inhabitant of plastic in the *perfect sorting* scenarios in figure 5.23 changes from a positive to a negative value, as the only of the investigated fractions. This proves that an increased material recycling of plastic is important for the environmental performance of the system. Plastic is therefore considered a critical waste fraction in terms of system performance and recommended measures. Figure 5.24 shows the total net climate impact per waste type in kg CO2-equivalents for the different scenarios over time. It seems like the scenarios with central sorting are the only scenarios where the plastic waste flow has a net positive value for the climate impact, which implies that the activities of the treatment of plastic waste emits more than it avoids. This is misleading, as figure 5.25 shows. This is a result of the modelling. For simplicity, the waste flows of residual waste and plastic waste were not combined to one common flow, as the situation in reality would have been. This only affects the results of the plastic flow, but not the plastic fraction. Compared to the *reference scenario*, more of the plastic in the plastic flow is now sent to incineration, whereas much less of the plastic in the residual flow is sent to incineration. The total of these two waste flows combined, shows that 18% less plastic is actually sent to incineration with central sorting than without. This can been seen in figure 5.25 where the plastic fraction in the *central sorting* and *all scenarios* scenario, has higher avoided emissions than the *reference scenario* in the same year.

As mentioned previously, organic waste also represents a critical fraction. A large share of the organic waste is sorted into the rest waste flow, as seen in figure 4.3, and is therefore not utilised in biogas and fertiliser production. Organic waste lowers the average calorific value of the rest waste and results in decreased energy recovery, assuming that the furnace can withstand higher temperature as a consequence of less organic material. It is also important to keep the organic waste separated from the plastic waste, as it contaminates the plastic and makes it unsuitable for recycling. A central sorting facility with less organic waste has a higher sorting efficiency for plastic waste. Better sorting of organic waste leads to better sorting of plastic waste and increased material recycling for both fractions as well as less waste sent to incineration. As incineration is the greatest contributor to GHG emissions, this will, together with increased material recycling of organic waste and plastic, eventually lead to a decrease in the climate impact of the system. The energy efficiency will most likely be lower, despite of increased biogas production, as there is less energy recovered through incineration, but it is likely that the overall environmental performance of the system will be improved.

**Environmental performance indicators.** In this thesis, GHG emissions in CO2-equivalents are the only indicator of environmental performance. Other important indicators like toxicity or water use have not been considered. An example is recycling of organic waste. It requires a lot of liquid, often water which of course affects the water use, although some treatment facilities combine organic household waste with manure to achieve the right liquid content for the anaerobic process. The residual of the biomethane production can be used as fertiliser, and consequently avoids production of artificial fertilisers and ensures the recovery of limited resources like phosphorus. These aspects affect the environmental performance of the organic waste fraction and the system as a whole, but are not included in this analysis. Including more indicators would most likely affect the results and chosen measures, but it would also complicate the modelling and data collection greatly.

The discussion of the environmental performance indicators, critical fractions and critical processes as conducted within the previous paragraphs leads to the findings that are relevant to answer the third research question, emphasising on the critical factors of the system in terms of environmental performance. As mentioned above, GHG emissions in CO2-equivalents are the examined indicator of environmental performance within this thesis. The results as discussed in the previous paragraphs showed that the climate impact is mainly influenced by chosen CO2 emission factors in general and emissions from the incineration process. The critical fractions turned out to be plastic and organic waste. Additionally to just the fractions themselves, the emissions caused by them can highly be influenced by the sorting efficiency, as for example the central sorting facility leads to a higher degree of sorting that resulted in higher avoided emissions and thus an improvement of the environmental performance.

## 6.2 Agreement with Literature

The assumption of continued growth in generated waste volumes differs from the waste statistics of Eurostat and SSB, as presented in chapter 2.2, but these statistics are on a national level and the Eurostat statistics include more than just household waste. [Eurostat, 2017] [SSB, 2016a] The assumed growth used in the modelling is based on calculations from the report "Fremtidens kildesortering i Drammensregionen" made specifically for the RfD region. [RfD, 2012]

The white paper proposal of the Norwegian Ministry of Climate and Environment highlights organic and plastic as critical fractions with potential for improvement. [KLD, 2017] The EC proposals also target plastic waste and food waste. [Borzan, 2016][EC, 2015b] This is in line with the results of the modelling in this thesis, where plastic and organic waste are recognised as critical fractions for the environmental performance of the waste management system of RfD.

The results of this modelling concluded that increased material recycling resulted in smaller climate impacts for all waste fractions. Similar conclusions were made in the Prognos report. [Prognos AG, 2008] Both the WRAP study and the Østfoldforskning study stated that material recycling is the best treatment option for plastic waste from an environmental point of view. [Michaud, 2010] [Raadal, 2009]

The most common way to measure environmental performance of a waste management system is through climate accounting, the net GHG emissions of the system, as done in this analysis. Most relevant studies use this indicator, although some argue that other indicators like toxicity or water use also should be investigated. [Michaud, 2010] [Raadal, 2009] [Laitala, 2012] [Prognos AG, 2008] [Skogesal, 2017] [Nessjøen, 2015]

It has been difficult to find relevant and comparable literature as the field of study just recently has been brought to broader attention.

## 6.3 Strengths and Weaknesses

### 6.3.1 The Model

**Strengths:** An important strength of the model is its generic architecture, thus it can be applied to different urban waste management systems. The model is very transparent, flexible and mass balance consistent. This allows for the model to be updated and developed further, to go deeper into certain areas of the system or add additional layers, as a cost layer.

After the reference system first is modelled, it is technically easy to implement other scenarios, if the necessary data is available. The model as it is now, provides an excellent overview of the material flows and an adequate representation of the energy flows and resulting emissions in the system. The model facilitates the investigation of dependencies in a very complex system. It is possible to define unambiguously indicators in the model and thus easily compare the system performance to relevant policy targets. The model can therefore be used as a planning tool for waste companies and municipalities.

**Weaknesses:** The lack of a cost layer in the analysis is an obvious weakness of the model and of the work. It was left out of the analysis in agreement with the supervisors due to time limitations. Material recycling and environmental performance are not the only performance criteria of a waste management system, costs are very important for the results and to decide on the right measures for the future. Other criteria like degree of service, costumer satisfaction and hygiene, to mention some, also affect the results and are important to the company, but are not included in the model. The modelled scenarios have been chosen to enable clear conclusions concerning the effects of the different measures examined. These scenarios may therefore not be necessarily realistic over time, but as scenarios are easily changed and added into the model, variations and adjustments can always be applied.

The model is still quite difficult to use and requires an extensive explanation, especially of the energy layer and the emission layer. If the intention for the tool is to make it available and easy to use for waste treatment companies, it might be smart to consider Excel as the only calculation platform. Matlab is highly unknown to commercial businesses and they are often not in the possession of necessary licenses. Errors are also difficult to track down if the person is not familiar with programming. If there is something wrong with the input in Excel, Matlab will display error codes that do not immediately point to the fact that the mistake is in Excel. It sometimes requires extensive knowledge about both programming in Matlab and the formulas in Excel to discover where the error is and how to fix it.

To calculate the energy used in the transportation, you have to calculate the energy intensity for each specific distance and fuel type. These calculations are done manually, outside the model. These results are then highly dependant on the individual's chosen conversion factors. These calculations also separate between different collection technologies. The data available, for instance route distance and collected weight, therefore has to be allocated between these technologies based on an assumption.

Furthermore, the detail level in the model can differ from the detail level of the available data within the considered use case. Some areas in the model are more detailed than available data allows, whereas other areas are based on very general assumptions. The model still presents a nice overview of the whole system, but the further downstream in the processes you go, the uncertainty grows and the generalized assumptions become more dominant. I would therefore not recommend to use the results as the only basis for decision making, not as they are now. Further refinement to the model on the one hand and a more complete and detailed data set from from the respective use case on the other hand will reduce the assumptions and uncertainties and therefore lead to more reliable and robust conclusions.

### 6.3.2 Data and Assumptions

The collection of data has been very difficult and time consuming, because of limited comparable literature on the field and the high number of detail in the modelling. The number of waste flows and fractions as well as the number of processes and of course the layers of the model, make up a very complex system which requires a lot of data from different sources. This affected the modelling, because the lack of data lead to assumptions and the use of dummy data, but also because it left shorter time for the modelling itself.

Of the three layers, the data foundation of the material layer is the most detailed and has the least amount of assumptions and average data, as RfD could provide much of the key data. The data used in the energy layer is based on many assumptions and average values, especially for the energy consumption of the different processes. It was very difficult to obtain specific process data, because the data was often unavailable and many of the waste treatment processes were divided between several facilities, and not just one per waste fraction. Most of the values for energy use for the different processes were collected from Ecoinvent. This leads to high uncertainties when it comes to the energy flows and the energy efficiency of the system. Consequently, the emission layer has a proportional level of uncertainty, as the emissions are calculated based on energy consumption and CO2 emission factors. As a result, the material recycling rates are the most robust results and the energy efficiencies and climate impacts are more uncertain.

As proven in the sensitivity analysis and discussed in previous paragraphs, the emission results are highly dependant on CO2 factors. The CO2 emissions factors are dependant on the assumed substituted material and energy in the specific process. There are, as of yet, no standardised values for these factors, and they might change with further research on the subject. The emissions are also highly dependant on the specific situation of the processes, geography for instance, influence parameters like energy mix, transportation distances and available treatment technologies. Norway and the Nordic countries have carbon low energy mixes compared to many other countries, which usually has a positive impact on the environmental performance. On the other hand, the plastic waste is sent from Norway to recycling facilities in Germany, which leads to a very high transportation distance for plastic compared to the other waste fractions.

The energy use and emissions connected to transportation is also based on many assumptions and average data, especially the downstream transportation. The data foundation and assumptions as well as method of calculation are further explained in the transportation section in appendix A. The energy consumed by transport makes up about 5% of the overall energy consumption of the system, while the GHG emissions make up around 15% for all scenarios. This means that although there is uncertainty connected to the transportation results, they do not have a great impact on the overall environmental performance of the system.

Detailed background data and assumptions made can be found in appendix A. The complete model, data sets and result files can be found in the separately attached appendix B.

### 6.3.3 The Work

It has to be mentioned that the work does not fulfill the project assignment to the full extent. In agreement with the supervisors, the cost layer of the model was excluded, as there was not enough time.

The communication with RfD has been consistently good and enjoyable and RfD has expressed its interest in the project and the outcomes. RfD and Mepex have provided valuable data that has increased the quality of the work. The cooperation has been successful and both sides have hopefully learned and benefited from each other.

The work has given an adequate representation of an urban waste management system and will hopefully prove to be useful for RfD and other waste management companies in the future. It has been interesting to see how a real existing system can be depicted in a model and that this model can be used to draw conclusions on system performance and recommended measures.

It is important to mention the invaluable help and guidance from student Pieter Callewaert who developed the model. At times it was very difficult to use and adapt a model made by someone else and parts of the time has been a model still under development, but it was the wish of the supervisor that all three case studies used the same model. As the model was being developed to include an energy layer and an emission layer in the early spring of 2017, it was not possible to start the modelling until after this was done. A positive outcome of using the same model for all case studies, is of course that it enables comparison across cases. This is necessary in the development of a generic planning tool, but has also proved to be helpful in the writing of this thesis. Common meetings and discussions with the two other students and the supervisors about the model and the waste management system have been very useful. As this thesis is written by one person alone, exchanges of information and discussions with the students Pieter Callewaert and Silje Unander have been most helpful and necessary.

The sensitivity analysis within the model did not work properly, and the author was unable to find and correct the error. As a consequence, the sensitivity analysis has been carried out by manual calculations and hence became more complicated and time consuming than expected. This resulted in a less comprehensive sensitivity analysis than planned.

A weakness of the work, as discussed and mentioned several times in the thesis, is that various assumptions had to be made because of an incomplete set of provided data, leading to inaccuracies. These dummy values or average data need to be replaced by actual data or more precise data in future research.

## 6.4 Implications for Policies and Future Research

### 6.4.1 Implications for Policies

Plastic waste has been marked as a critical fraction when it comes to the system's environmental performance. The results clearly state the importance of an increased material recycling for the plastic waste fraction and thereby support the necessity of new ambitious targets as proposed by the EC and the Norwegian Ministry of Climate and Environment. The results also support the suggested targeting of organic waste.

Sorting is recognized as a critical factor for increased material recycling and improved environmental performance, for all fractions, but especially for plastic and organic waste. There are different possible measures that can improve this critical factor and they should be investigated further and hopefully also be implemented in policies to ensure a successful outcome. Some measures have already been suggested, like obligatory sorting of organic waste at source. This will not only improve the sorting and thereby the recycling rate of organic waste, it will also increase the amount of plastic waste suited for recycling as there is less contamination as well as lead to higher temperatures in incineration furnaces and higher relative energy recovery. Another consequence of sorting of organic waste in the households might be increased awareness concerning food waste, which is an important step towards the suggested targets of reduced amounts of food waste in the society. These measures are therefore recommended by the author.

The results of the modelling show that biogenic fuels have a positive climate impact, as long as biogenic emissions are considered carbon neutral. This means that vehicles fuelled by biogenic fuels, as well as the production of such fuels, is recommended to be encouraged, substituted or even made mandatory for public services, from an environmental point of view.

Incineration is a very critical process when it comes to both energy recovery and emissions. Improvement in technology might increase the energy recovery rate as well as lower the emissions. Incineration plants with emission control and CO2 capturing technology will improve the environmental performance of the waste management system significantly. It is therefore recommended to encourage and facilitate research and development in these technologies.

CO2 emission factors have been proven to have a great impact on the environmental performance of the waste management system. Is is therefore recommended to research this topic further and seek to agree on commonly acknowledged and standardised emission factors and frameworks to calculate and report on environmental performance, not only for waste management systems, but in general terms of environmental research.

## A Implications for RfD

**Implications.** As mentioned in chapter 2.1.2, RfD has two very specific targets for the performance of its waste management system. The first target is to have a total net climate gain of 100 000 tonne CO2-equivalents. The *perfect sorting* scenarios were the only scenarios where the total net climate impact had negative values, which means a net reduction of emissions, as shown in figure 5.24. However, as figure 5.25 shows, the activities in the waste management system contribute to considerable amounts of avoided emissions. It is important to note that household waste and the investigated fractions only make up a part of the total waste amounts and responsibilities of RfD. As mentioned before, household waste is especially difficult to material recycle because of its composition. Consequently, this analysis can not conclude on the achievement of RfD's overall objectives. This also applies to the target of only 30% of the waste being sorted as residual waste. Figure 5.7 shows that more than half of the generated waste amounts end up in an incineration facility, which is a pointer to what the waste has been sorted to and collected as. Again, this analysis accounts for only a small part of the total waste quantities, and therefore can not draw conclusions regarding the total proportion of residual waste in RfD's waste management system.

**Recommended measures.** Areas with potential for improvement and critical factors for the environmental performance of RfD's waste management have been found. First of all, the measure already taken by RfD, to have collection vehicles fueled by biogas, has proven to have a positive impact on the environmental performance. The scenarios including this measure have lower transport emissions than the other scenarios in the same year, see figure 5.26. The total net impact of the system is also lower than for the comparable scenarios, expect for the highly theoretical scenario of *perfect sorting*.

To further improve the environmental performance of the system, the sorting and thereby the recycling of plastic waste should be improved. This can be done by including a central sorting facility for the sorting of the residual waste. The organic waste should still be sorted separably at source, as this improves the recycling rates of plastic due to less contamination. Apart from the *perfect sorting scenario*, the scenarios including a central sorting facility have the lowest total net climate impact, as seen in figure 5.24.

In line with proposals of both the EC and the Norwegian Ministry of Climate and Environment, RfD should also target organic waste. An improved sorting of organic waste in the households will improve the sorting and consequently the material recycling of plastic, produce more biogas and fertiliser, reduce the amounts sent to incineration as well as improving the relative energy recovery of the incineration as long as the technology allows higher temperatures, all of which will have a positive impact on the climate impact of the system. RfD can, in cooperation with other relevant agencies, organisations and ministries, inform and raise awareness about and encourage improved sorting of organic waste. A campaign like this can also target food waste prevention, in line with the waste hierarchy and proposals of EC and the Norwegian Ministry of Climate and Environment.

The last recommended measure for RfD concerns the transportation of waste to the collection parks. These emissions do not affect RfD's climate impact, but are still an important factor in the transport emissions in the system. RfD can encourage and facilitate reductions of these emissions by limiting some of the parameters affecting the transport, like the transport distance or the transported waste amounts. This can be done by increased collection at source for certain fractions with services like waste ”taxis”, as an example.

The *all scenarios* scenario has the most positive net climate impact, apart from the highly theoretical *perfect sorting* scenario. Consequently, along with the fact that it incorporates already recommended measures, this scenario is recommended to be the guideline for RfD's future strategies. Finally, it is important to point out that recommended measures also depend on financial considerations that have not been included in this assessment.

### 6.4.2 Recommendations for Future Research

A cost layer should be implemented in the model, as the financial aspect affect the extent of the measures as well as which measures that will be implemented. Environmental friendly measures will not be taken at all costs. There has to be a balance between costs and environmental performance. A cost layer in the model is necessary to better choose the most favorable and effective measures.

The model is still quite complicated to use and there are little or no explanations embedded in the model. If the objective is to make a model that can be used by the waste management industry, it needs to be more documented and user friendly. A further development of the model by Pieter Callewaert is already planned for the summer of 2017, which the author believes will improve the model's user friendliness drastically. Communication with intended future users, waste management companies, can be helpful in the future development of the model.

As mentioned previously, the data collection has been time consuming, at times difficult and somewhat uneven. A further data collection may even out the level of detail in the model and increase the accuracy of the results. The share of assumptions and generic or averaged data should be lowered, as this leads to uncertainties. More specific data is expected to lead to more precise and conclusive results that enable a more precise and applicable interpretation. This can be achieved by a closer and sustainable cooperation with all parties involved in a mid-term perspective.

A more comprehensive sensitivity analysis to better understand the impact of CO2 emissions factors is recommended. As there are no official recommendations or regulations on CO2 emission factors, these factors can be chosen strategically to influence the results for a desired outcome. This, as mentioned previously, states the importance of commonly acknowledged and standardised emission factors and frameworks to calculate and report on environmental performance, not only for waste management systems, but in general terms of environmental research.

# Chapter 7

# Conclusion

The objective of this work was to analyse the environmental performance and critical improvement factors of urban waste management systems. This has been done in collaboration with and by conducting a case study of the urban waste management system of RfD, an organisation collecting the municipal solid waste from the households in the Drammen region.

The literature study resulted in providing the necessary theoretical background. Fundamental terms have been defined and the characteristics and legislation of waste management systems, material flow analysis and environmental performance in waste management have been singularised. After having described the utilised model, the case study and the examined company have been introduced and system boundaries, constituent processes, flows and fractions have been determined. The model has been applied for six scenarios and compared for the years 2015, 2025 and 2030.

The model has depicted the system adequately, although there are uncertainties connected to the energy and emissions layer especially. The results seems credible and are in line with relevant research literature and current and proposed legislation. The first research question question was: *How do measures motivated by circular economy influence the material recycling rate of the different materials in the system?* The circular economy requires extensive material recycling and measures that improve the material recycling rates are important. The results showed that sorting is a critical factor for the material recycling efficiency for all waste fractions, but especially for plastic and organic waste. Metal, glass and paper and cardboard already have a relatively high degree of sorting and thus material recycling. The sorting can be improved by implementing a central sorting facility for residual and plastic waste in the system. Better sorting at source and separate sorting and collection of organic waste also proved to be important.

The second research question was: *How do the measures for increased material recycling affect the energy consumption and GHG emissions of the system?* The results showed a general trend towards increased material recycling leading to lower energy efficiency, but also lower emissions due to less incineration and more avoided virgin material production.

The last research question was: *What are the critical factors of the system in terms of environmental performance?* The environmental performance was measured in net climate impact in kg CO2-equivalents. As GHG emissions are closely connected to material recycling and energy use, plastic and organic waste have been recognized as critical waste fractions. These fractions have a high impact of the emissions of the system and also have great potential for improvement. Other critical factors are the degree of sorting, due to the impact on material recycling rates, and the incineration process, as it produces more than half of the GHG emissions in the system for most scenarios.

CO2 emission factors also proved to be critical for the environmental performance of the system. The importance of commonly acknowledged emission factors and frameworks to calculate and report on environmental performance, not only for waste management systems, but in general terms of environmental research, is underlined.

Based on the results of the analysis, RfD is recommended to improve the sorting in the system by implementing a central sorting facility and encourage better sorting in the households. The transition to collection vehicles fulled by biogas has been proven to have a positive impact on the environmental performance of the waste management system of RfD. These combined measures were tested in the *all scenarios* scenario, which was the realistic scenario with the lowest negative climate impact.

This work focused on examining GHG emissions as environmental performance indicator. GHG emissions affect the environment in terms of climate change. Other environmental performance indicators like toxicity, water use, etc are not investigated here. Nevertheless, to achieve a holistic picture regarding the total environmental performance, they should not be left out by academic research.

This work contributes to the field of environmental engineering by demonstrating the application of a model to assess the environmental performance and critical improvement factors of urban waste management systems. The case study as conducted in collaboration with RfD proved the applicability of the model and led to the findings, conclusions and future recommendations as formulated above, that may serve as inspiration for future academic research.

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# Appendix A

# Background Data

## A.1 General Assumptions and Data for All Scenarios

### A.1.1 Main Assumptions

**The Material Layer:**

- The population growth, based on calculations by Asplan Viak.

- The growth in waste amounts, based on calculations by Asplan Viak.

- The degree of sorting for underground solutions, based on several picking analyses from RfD and TRV.

- The percentage of collection technologies, based on resident types and national trends.

- The glass and metal collected were assumed to be 1/3 metal and 2/3 glass when separated into glass and metal.

- Losses in the flows from one process to another were often assumed to be zero or very small.

- Recycling rates for the material recycling was partly based on personal communication between Pieter Callewaert and Ragn-Sells AS and partly assumed where necessary data was not available.

**The Energy Layer:**

- Several assumptions were made in the collection transport calculations, see the transport section.

- The energy consumption if the different processes were collected from Ecoinvent or based on assumptions.

## A.1.2 General Data

The ash content of the combustion process was based on data from the book "Solid Waste Technology and Management" [Christensen, 2011]. Figure A.1 shows the numbers used in the model. The numbers represent the share of the fraction coming out of the incineration.

| | Transfer coef | Unit | G&M | Org. | Rest | P&C | Plast. |
|---|---|---|---|---|---|---|---|
| **Transfer Coef** | **T811** | | | | | | |
| Glass | | % | 0,97 | 0,97 | 0,97 | 0,97 | 0,97 |
| Metal | | % | 0,94 | 0,94 | 0,94 | 0,94 | 0,94 |
| Organic | | % | 0,13 | 0,13 | 0,13 | 0,13 | 0,13 |
| Rest | | % | 0,10 | 0,10 | 0,10 | 0,10 | 0,10 |
| P&C | | % | 0,56 | 0,56 | 0,56 | 0,56 | 0,56 |
| Plastics | | % | 0,02 | 0,02 | 0,02 | 0,02 | 0,02 |
| Hazardous | | % | 0,10 | 0,10 | 0,10 | 0,10 | 0,10 |
| Textiles | | % | 0,04 | 0,04 | 0,04 | 0,04 | 0,04 |

**Figure A.1:** Screen-dump from the model showing the assumed ash content.

It was assumed that 99% of the metal in bottom ash treatment was sent to material recycling.

The different values used to calculate the recycling rates used in the model are mostly based on assumptions. Some of the values have been provided by Ragn-Sells AS via personal communication with Pieter Callewaert [Ragn-Sells, 2016]. Table A.1 shows the values used in the modelling of the material recycling.

In the biological treatment facility it was assumed that 16% was sent to incineration, 56% utilised in biogas production and 28% ended up in fertiliser production.

| | Transfer coef | G&M | Org. | Rest | P&C | Plast. |
|---|---|---|---|---|---|---|
| **Transfer Coef** | **T98** | | | | | |
| Glass | | 0,00 | | 0,00 | 1,00 | 1,00 |
| Metal | | 0,00 | | 0,00 | 1,00 | 1,00 |
| Organic | | 1,00 | | 0,00 | 1,00 | 1,00 |
| Rest | | 1,00 | | 1,00 | 1,00 | 1,00 |
| P&C | | 0,03 | | 0,03 | 0,03 | 0,03 |
| Plastics | | 1,00 | | 1,00 | 1,00 | 0,05 |
| Hazardous | | 0,00 | | 0,00 | 0,00 | 0,00 |
| Textiles | | 1,00 | | 0,00 | 1,00 | 1,00 |

**Figure A.2:** Screen-dump from the model showing the transfer coefficient T98.

| | Transfer coef | G&M | Org. | Rest | P&C | Plast. |
|---|---|---|---|---|---|---|
| **Transfer Coef** | **T68** | | | | | |
| Glass | | 0,01 | | | | 1,00 |
| Metal | | 0,01 | | | | 1,00 |
| Organic | | 1,00 | | | | 1,00 |
| Rest | | 0,39 | | | | 0,39 |
| P&C | | 1,00 | | | | 1,00 |
| Plastics | | 1,00 | | | | 0,20 |
| Hazardous | | 0,00 | | | | 0,00 |
| Textiles | | 1,00 | | | | 1,00 |
| **Transfer Coef** | **T610** | | | | | |
| Glass | | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| Metal | | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| Organic | | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| Rest | | 0,61 | 0,00 | 0,00 | 0,00 | 0,61 |
| P&C | | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| Plastics | | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| Hazardous | | 1,00 | 1,00 | 1,00 | 1,00 | 1,00 |
| Textiles | | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| **Transfer Coef** | **T69** | | | | | |
| Glass | | 0,99 | | | | 0,00 |
| Metal | | 0,99 | | | | 0,00 |
| Organic | | 0,00 | | | | 0,00 |
| Rest | | 0,00 | | | | 0,00 |
| P&C | | 0,00 | | | | 0,00 |
| Plastics | | 0,00 | | | | 0,80 |
| Hazardous | | 0,00 | | | | 0,00 |
| Textiles | | 0,00 | | | | 0,00 |

**Figure A.3:** Screen-dump from the model showing the transfer coefficients for process 6.

**Table A.1:** Material recycling values used in the model.

| Waste fraction | TC Value | |
|---|---|---|
| Metal in rest to recycling, burned | 0.1 | Assumption |
| Plastic in rest to recycling, burned | 0.1 | [Ragn-Sells, 2016] |
| Paper in rest to recycling, burned | 0.025 | [Ragn-Sells, 2016] |
| Paper in paper to recycling, burned | 0.025 | [Ragn-Sells, 2016] |
| Plastic in G&M, burned | 1 | Assumption |
| Paper in G&M, burned | 1 | Assumption |
| Rest in G&M, burned | 0.5 | Assumption |
| Rest in G&M, landfilled | 0.5 | Assumption |
| Glass in G&M, recycled | 1 | Assumption |
| Metal in G&M, recycled | 1 | Assumption |

## A.2 The More Underground Scenario

Figure A.4 shows the assumed degree of sorting for the small and larger collection containers, as used for the diagram in figure 4.3. Figure A.5 shows the assumed degree of sorting for the underground collection containers.

| | G&M | Org. | Rest | P&C | Plast. |
|---|---|---|---|---|---|
| Glass | 0,57 | 0,0026667 | 0,036 | 0,001333 | 0,004 |
| Metal | 0,29 | 0,0013333 | 0,018 | 0,000667 | 0,002 |
| Organic | 0,00 | 0,944 | 0,305 | 0,008 | 0,012 |
| Rest | 0,12 | 0,022 | 0,367 | 0,01 | 0,123 |
| P&C | 0,00 | 0,01 | 0,094 | 0,973 | 0,025 |
| Plastics | 0,00 | 0,016 | 0,107 | 0,008 | 0,824 |
| Hazardous | 0,01 | 0,004 | 0,013 | 0 | 0,003 |
| Textiles | 0,00 | 0 | 0,062 | 0 | 0,008 |

**Figure A.4:** Screen-dump from the model showing the assumed degree of sorting for the small and larger collection containers.

| | G&M | Org. | Rest | P&C | Plast. |
|---|---|---|---|---|---|
| Glass | 0,544 | 0,003 | 0,036 | 0,001 | 0,004 |
| Metal | 0,272 | 0,001 | 0,018 | 0,001 | 0,002 |
| Organic | 0,000 | 0,900 | 0,305 | 0,008 | 0,052 |
| Rest | 0,171 | 0,066 | 0,367 | 0,050 | 0,123 |
| P&C | 0,000 | 0,010 | 0,094 | 0,933 | 0,055 |
| Plastics | 0,000 | 0,016 | 0,107 | 0,008 | 0,754 |
| Hazardous | 0,013 | 0,004 | 0,013 | 0,000 | 0,003 |
| Textiles | 0,000 | 0,000 | 0,062 | 0,000 | 0,008 |

**Figure A.5:** Screen-dump from the model showing the assumed degree of sorting for the underground solutions.

# A.3 The Biogas Scenario

| | | G&M | | Org. | | Rest | | P&C | | Plast. | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | % | Kwh/tkm | % | Kwh/t | % | Kwh/t | % | Kwh/t | % | Kwh/t |
| små | **X01** | | | | | | | | | | |
| | Diesel | 0,00000 | 0,01462 | 0,00000 | 0,02186 | 0,00000 | 0,00910 | 0,00000 | 0,00883 | 0,00000 | 0,06474 |
| | Biometha | 1,00000 | 0,01117 | 1,00000 | 0,01671 | 1,00000 | 0,01671 | 1,00000 | 0,00675 | 1,00000 | 0,04949 |
| cont | **X01** | | | | | | | | | | |
| | Diesel | 0,00000 | 0,02505 | 0,00000 | 0,03747 | 0,00000 | 0,01560 | 0,00000 | 0,01514 | 0,00000 | 0,11099 |
| | Biometha | 1,00000 | 0,01915 | 1,00000 | 0,02865 | 1,00000 | 0,02865 | 1,00000 | 0,01157 | 1,00000 | 0,08485 |
| ned | **X01** | | | | | | | | | | |
| | Diesel | 0,00000 | 0,17538 | 0,00000 | 0,26230 | 0,00000 | 0,10918 | 0,00000 | 0,10599 | 0,00000 | 0,77693 |
| | Biometha | 1,00000 | 0,13407 | 1,00000 | 0,20052 | 1,00000 | 0,20052 | 1,00000 | 0,08102 | 1,00000 | 0,59392 |
| sug | **X01** | | | | | | | | | | |
| | Diesel | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 |
| | Biometha | 1,00000 | 0,00000 | 1,00000 | 0,00000 | 1,00000 | 0,00000 | 1,00000 | 0,00000 | 1,00000 | 0,00000 |

**Figure A.6:** Screen-dump from the model showing the energy intensity of the collection vehicles.

## A.4 The Central Sorting Scenario

| | Transfer coef | G&M | Org. | Rest | P&C | Plast. |
|---|---|---|---|---|---|---|
| **Transfer Coef** | **T27** | | | | | |
| Glass | | 0,00 | 0 | 0 | 0 | 0 |
| Metal | | 0,00 | 0 | 0 | 0 | 0 |
| Organic | | 0,00 | 0 | 0 | 0 | 0 |
| Rest | | 0,00 | 0 | 0 | 0 | 0 |
| P&C | | 0,00 | 0 | 0 | 0 | 0 |
| Plastics | | 0,00 | 0 | 0 | 0 | 0 |
| Hazardous | | 0,00 | 0 | 0 | 0 | 0 |
| Textiles | | 0,00 | 0 | 0 | 0 | 0 |
| **Transfer Coef** | **T28** | | | | | |
| Glass | | 0,00 | 0 | 1 | 0 | 1 |
| Metal | | 0,00 | 0 | 0,12 | 0 | 0,12 |
| Organic | | 0,00 | 0 | 0,97 | 0 | 0,97 |
| Rest | | 0,00 | 0 | 0,98 | 0 | 0,98 |
| P&C | | 0,00 | 0 | 0,59 | 0 | 0,59 |
| Plastics | | 0,00 | 0 | 0,5 | 0 | 0,5 |
| Hazardous | | 0,00 | 0 | 1 | 0 | 1 |
| Textiles | | 0,00 | 0 | 1 | 0 | 1 |
| **Transfer Coef** | **T29** | | | | | |
| Glass | | 0,00 | 0 | 0 | 0 | 0 |
| Metal | | 0,00 | 0 | 0,88 | 0 | 0,88 |
| Organic | | 0,00 | 0 | 0,03 | 0 | 0,03 |
| Rest | | 0,00 | 0 | 0,02 | 0 | 0,02 |
| P&C | | 0,00 | 0 | 0,41 | 0 | 0,41 |
| Plastics | | 0,00 | 0 | 0,5 | 0 | 0,5 |
| Hazardous | | 0,00 | 0 | 0 | 0 | 0 |
| Textiles | | 0,00 | 0 | 0 | 0 | 0 |

**Figure A.7:** Screen-dump from the model showing the assumed degree of sorting in the central sorting scenario.

## A.5 The Perfect Sorting Scenario

| | Flow/tech | G&M | Org. | Rest | P&C | Plast. |
|---|---|---|---|---|---|---|
| **flow** | **X01** | 3967,4 | 17897,8 | 12302,0 | 12757,9 | 4163,1 |
| Technology: | småbeholdere | 0,60 | 0,60 | 0,60 | 0,60 | 0,60 |
| Glass | | 0,67 | 0 | 0 | 0 | 0 |
| Metal | | 0,33 | 0 | 0 | 0 | 0 |
| Organic | | 0,00 | 1 | 0 | 0 | 0 |
| Rest | | 0,00 | 0 | 0,8365286 | 0 | 0 |
| P&C | | 0,00 | 0 | 0 | 1 | 0 |
| Plastics | | 0,00 | 0 | 0 | 0 | 1 |
| Hazardous | | 0,00 | 0 | 0,0338818 | 0 | 0 |
| Textiles | | 0,00 | 0 | 0,1295896 | 0 | 0 |

**Figure A.8:** Screen-dump from the model showing the assumed degree of sorting.

## A.6 Transportation

**Table A.2:** Energy factors used for the transportation calculations.

| Factor | Value | Unit | Reference |
|---|---|---|---|
| Diesel, energy content | 9,9722 | kWh/l | [Frischknecht, 2005] |
| Diesel, energy consumption | 0,43 | l/km | [RenoNorden, 2017] |
| Biomethane,energy content | 9,67 | kWh/nm3 | [bio, 2017] |
| Biomethane, energy consumption | 0,6 | nm3/km | [RenoNorden, 2017] |

Some of the waste types are collected in the same collection vehicle. Paper and cardboard and plastics are collected in the same vehicle 13 times a year. Organic waste and residual waste is also collected in the same vehicle, on average 32,5 times a year. Glass and metal is collected 6 times a year. The route distances are therefore allocated between the different waste types collected on the same trip. Allocation by weight percentage was considered, but in the end the route distances were divided equally between the waste types collected in the same vehicle. This was done to simplify the calculations so that this would not have to be redone for all the different scenarios, if the waste composition changed. When it comes to technology, the weight and the route distance is allocated between the different collection technologies. The allocation is the percentage presented in table 4.3. Collection frequency and transport distances were collected from the climate accounting of Mepex. [Skogesal, 2017]

For the waste brought to the collection parks it is assumed an average transport distance of 14 km that is based on a questionnaire from the climate accounting of Mepex. [Skogesal, 2017] The number of visits is also taken from this tool. These numbers are from year 2016, but it is assumed the same numbers for 2015. The distance is assumed the same for all waste types, but the number of visits (collection frequency) is allocated according to the percentage of the waste delivered in total and the number of visits, turned out to be the same. The total of these waste types, not in general. Then the equations in chapter 3.4.2 are used to calculate the energy intensity of the transport. Even though this transport is done with personal vehicles, that usually run on petrol fuel and not diesel, diesel is assumed to be the energy carrier for simplification in the model. Diesel is one of the main energy carriers/fuels in the model, and seeing as this is the only transportation done with personal vehicles and it is a very small part of the total transportation, the assumption is justified. If the calculations were done with regular fuel, the energy use and emissions would most likely be a little lower in this specific process. It is also assumed that none of the personal vehicles use biomethane as fuel.

It is assumed that the route distances, the collection frequency and the efficiency of the collection trucks/energy consumption does not change from year to year. Apart from the scenario where all the collection vehicles run on biogas.

The transport distances to the reloading stations are estimated using google maps. The reloading station called Lindum is used in the estimations, as this reloading station has around 70 % of the activity. Some of the distances are also taken from the climate accounting excel sheet made by Mepex for RfD. [Skogesal, 2017]

| | | | | | | |
|---|---|---|---|---|---|---|
| X01 | 8586 | 4293 | 4293 | 6594,9 | 6594,9 | |
| X01 | 5008,5 | 2504,25 | 2504,25 | 3847,025 | 3847,025 | |
| X01 | 715,5 | 357,75 | 357,75 | 549,575 | 549,575 | |
| X01 | 0 | 0 | 0 | 0 | 0 | |
| X12 | 0 | 0 | 0 | 0 | 0 | |
| X42 | 0 | 0 | 40 | 0 | 40 | |
| X52 | 0 | 0 | 0 | 0 | 0 | |
| X03 | 0 | 0 | 0 | 0 | 0 | |
| X03 | 0 | 0 | 0 | 0 | 0 | |
| X03 | 0 | 0 | 0 | 0 | 0 | |
| X14 | 25 | 25 | 25 | 25 | 25 | |
| X34 | 0 | 0 | 0 | 0 | 0 | |
| X54 | 25 | 25 | 25 | 25 | 25 | |
| X05 | 14 | 14 | 14 | 14 | 14 | |
| X36 | 0 | 0 | 0 | 0 | 0 | |
| X46 | 109 | 0 | 0 | 0 | 1046 | |
| X56 | 0 | 0 | 0 | 0 | 0 | |
| X27 | 0 | 0 | 50 | 0 | 50 | |
| X47 | 0 | 55 | 0 | 0 | 0 | |
| X28 | 0 | 0 | 480 | 0 | 480 | |
| X48 | 0 | 0 | 480 | 0 | 0 | av |
| X68 | 154 | 0 | 0 | 0 | 154 | |
| X78 | 0 | 480 | 0 | 0 | 0 | as |
| X98 | 100 | 100 | 100 | 100 | 100 | as |
| X29 | 0 | 0 | 1046 | 0 | 1046 | |
| X49 | 0 | 0 | 0 | 500 | 0 | as |
| X69 | 500 | 0 | 0 | 0 | 0 | as |
| X610 | 100 | 0 | 0 | 0 | 100 | |
| X910 | 100 | 0 | 0 | 100 | 100 | as |
| X1110 | 128 | 128 | 128 | 128 | 128 | |
| X811 | 100 | 100 | 100 | 100 | 100 | as |
| X1112 | 100 | 100 | 100 | 100 | 100 | as |

**Figure A.9:** Screen-dump from the model showing the transport distances.

The energy intensity of the different energy carriers is not that different in kWh/km, but the values used in the model are very different. This is because the values are relative and are based on weight, transport distance and the allocation between different vehicle technologies. The values used for the collection from households can be seen in figure A.6. The energy intensities used for the other transport distances are shown in figure A.10. The downstream transport uses the values of 0,27281 or 0,427 based on the transported weight.

| | G&M | | Org. | | Rest | | P&C | | Plast. | |
|---|---|---|---|---|---|---|---|---|---|---|
| | % | Kwh/tkm | % | Kwh/t | % | Kwh/t | % | Kwh/t | % | Kwh/t |
| **X14** | | | | | | | | | | |
| Diesel | 0,00000 | 0,42700 | 0,00000 | 0,42700 | 0,00000 | 0,42700 | 0,00000 | 0,42700 | 0,00000 | 0,42700 |
| Biometha | 1,00000 | 0,05480 | 1,00000 | 0,08196 | 1,00000 | 0,08196 | 1,00000 | 0,03312 | 1,00000 | 0,24275 |
| **X34** | | | | | | | | | | |
| Diesel | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 |
| Biometha | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 |
| **X54** | | | | | | | | | | |
| Diesel | 1,00000 | 0,42700 | 1,00000 | 0,42700 | 1,00000 | 0,42700 | 1,00000 | 0,42700 | 1,00000 | 0,42700 |
| Biometha | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 |
| **X05** | | | | | | | | | | |
| Diesel | 1,00000 | 29,41712 | 1,00000 | 29,41712 | 1,00000 | 29,41712 | 1,00000 | 29,41712 | 1,00000 | 29,41712 |
| Biometha | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 |
| **X36** | | | | | | | | | | |
| Diesel | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 |
| Biometha | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 |
| **X46** | | | | | | | | | | |
| Diesel | 1,00000 | 0,27281 | 1,00000 | 0,27281 | 1,00000 | 0,27281 | 1,00000 | 0,27281 | 1,00000 | 0,27281 |
| Biometha | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 |
| **X56** | | | | | | | | | | |
| Diesel | 1,00000 | 0,42700 | 1,00000 | 0,42700 | 1,00000 | 0,42700 | 1,00000 | 0,42700 | 1,00000 | 0,42700 |
| Biometha | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 | 0,00000 |

**Figure A.10:** Screen-dump from the model showing the energy intensity of the different transportation vehicles.

# A.7 Energy

Process Energy (kwh/t)

| | 35,9 | 44 | | | |
|---|---|---|---|---|---|
| 0 | G&M | Org. | Rest | P&C | Plast. |
| 1 | | | | | |
| Electricity | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Diesel | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Heat | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Oil | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Natural gas | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| 2 | | | | | |
| Electricity | 0,0000 | 0,0000 | 42,9000 | 0,0000 | 42,9000 |
| Diesel | 0,0000 | 0,0000 | 1,5700 | 0,0000 | 1,5700 |
| Heat | 0,0000 | 0,0000 | 6,5000 | 0,0000 | 6,5000 |
| Oil | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Natural gas | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| 3 | | | | | |
| Electricity | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Diesel | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Heat | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Oil | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Natural gas | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| 4 | | | | | |
| Electricity | 0,0000 | 0,0000 | 0,0000 | 15,0000 | 0,0000 |
| Diesel | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Heat | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Oil | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Natural gas | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| 5 | | | | | |
| Electricity | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Diesel | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Heat | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Oil | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Natural gas | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| 6 | | | | | |
| Electricity | 18,0000 | 0,0000 | 0,0000 | 0,0000 | 18,0000 |
| Diesel | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Heat | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Oil | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Natural gas | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |

**Figure A.11:** Screen-dump from the model showing the process energy demand.

| | 35,9 | 44 | | | |
|---|---|---|---|---|---|
| 0 | G&M | Org. | Rest | P&C | Plast. |
| 7 | | | | | |
| Electricity | 0,0000 | 80,0000 | 80,0000 | 0,0000 | 0,0000 |
| Diesel | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Heat | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Oil | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Natural gas | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| 8 | | | | | |
| Electricity | 116,5757 | 116,5757 | 116,5757 | 116,5757 | 116,5757 |
| Diesel | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Heat | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Oil | 25,3377 | 25,3377 | 25,3377 | 25,3377 | 25,3377 |
| Natural gas | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| 9 | | | | | |
| Electricity | 221,0000 | 0,0000 | 660,0000 | 65,0000 | 660,0000 |
| Diesel | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Heat | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Oil | 0,4600 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Natural gas | 92,0000 | 0,0000 | 167,0000 | 1243,0000 | 167,0000 |
| 10 | | | | | |
| Electricity | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Diesel | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Heat | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Oil | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Natural gas | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| 11 | | | | | |
| Electricity | 10,0000 | 10,0000 | 10,0000 | 10,0000 | 10,0000 |
| Diesel | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Heat | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Oil | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Natural gas | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| 12 | | | | | |
| Electricity | 0,0000 | 0,0000 | 15,0000 | 0,0000 | 0,0000 |
| Diesel | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Heat | 0,0000 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| Oil | 0,0000 | 0,0000 | 4,6000 | 0,0000 | 0,0000 |
| Natural gas | 0,0000 | 0,0000 | 28,0000 | 0,0000 | 0,0000 |

**Figure A.12:** Screen-dump from the model showing the process energy demand.

# Appendix B

# The Model, further Data and Results

The model, further data and results used in this thesis can be found in the attached zip-file called ”Model 2.3 RfD”. This folder contains all the matlab-code as well as the necessary excel-files to run the model. It also contains the result files.