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Analysing the sustainability performance and critical improvement factors of urban municipal waste systems

case study RoAF

Pieter Guido Callewaert

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Supervisor: Helge Brattebø, EPT
Co-supervisor: Sigrun Jahren, EPT

Norwegian University of Science and Technology
Department of Energy and Process Engineering

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MASTER THESIS

for

Student Pieter Callewaert

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

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

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 RoAF (Romerike Avfallsforedling) 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 RoAF, with Øivind Brevik and Thomas Rem as contact persons, 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 RoAF'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 RoAF 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 thesis concludes my Master of Science in Industrial Ecology at the Norwegian University of Science and Technology, Department of Energy and Process Engineering.

In August 2016, I was given the opportunity to develop the theoretical model used in this project. We decided to share the model with other students conducting a similar project. To maximise the outcome of this, I guided the students in the process of using the model. Throughout the semester, the time-consuming process of collecting data was carried out and several visits at RoAF were necessary to complete this process. In close collaboration with my supervisor Helge Brattebø, it was decided to focus on material flows, energy consequences and emissions. An economic analysis is therefore not included in the thesis.

Several people have been involved in this project and supported my work. I would like to thank my supervisor Helge Brattebø for the excellent guidance throughout the semester and the opportunity he gave me to present this thesis to several organisations. Special thanks to Thomas Rem from RoAF for providing we with coffee, data, contact details and valuable feedback about the model. I would like to thank Tore Henie and Terje Skovly from RoAF for their collaboration in finding answers on all my detailed questions. I also wish to thank Øivind Brevik for the opportunity to carry out this project at RoAF. Finally, I would like to thank my girlfriend Ingunn Dising for introducing me to the Norwegian culture and giving me the motivation to learn Norwegian. This has proven to be very useful while conducting this work.

Sammendrag

Skiftet mot en sirkulær økonomi er en vesentlig faktor i kampen mot klimaendringer og utarming av ressurser. Som følge av dette vedtok den europeiske unionen en handlingsplan for sirkulær økonomi. Denne stiller flere krav til avfallsbransjen, blant annet skal 65% av husholdningsavfall materialgjenvinnes innen 2030. I tillegg er det fremmet forslag om 55% resirkulering av plastemballasje. Det framkommer i litteraturstudiet at Norge har et behov for systemevalueringsverktøy som kan støtte beslutninger som tas i avfallsbransjen.

Basert på materialstrømsanalyse har det blitt utviklet en modell for å evaluere et avfallssystem med hensyn til gjenvinningsgrad, energieffektivitet og utslipp. Modellen er testet på avfallssystemet til RoAF, som for øyeblikket er det eneste avfallsselskapet i Norge som sender restavfall gjennom et ettersorteringsanlegg. Denne praksisen anses som vesentlig for å oppnå EUs mål for sirkulær økonomi.

Analysen viser at innsamling av matavfall er avgjørende for å øke materialgjenvinningsgraden. I tillegg vil bedre innsamling ha en positiv effekt på plastsorteringen i anlegget, noe som medfører høye klimagevinster. For å nå det pålagte gjenvinningsmålet er det nødvendig å forbedre innsamlingen av alle typer avfall. Å implementere ettersorteringsanlegg vil ikke være tilstrekkelig for å oppnå 65%-målet. Det betraktes likevel som en effektiv strategi for å oppnå målet om 55% materialgjenvinning av plastemballasje. I hvilken grad et avfallsselskap vil ha fordeler av et ettersorteringsanlegg, er avhengig av deres nåværende avfallssystem.

Abstract

The shift towards a circular economy is a crucial factor to combat climate change and resource depletion. In this context, the European Union adopted the circular economy package resulting in different targets for the waste sector. One of these targets is a 65% recycling rate for municipal waste by 2030. Furthermore, a proposal for a 55% recycling target for plastic packaging was submitted in 2015. The literature study revealed a need for more system assessment tools to support decision making. Norway was identified as one of the countries that needs tools to rationalise their choices and to design effective strategies toward circularity.

A system assessment model was developed based on the principles of material flow analysis. The model was used to analyse the performance of the current waste management system of RoAF (Romerike Avfallsforedling) outside Oslo with respect to recycling, energy efficiency and emissions. RoAF is currently the only company that sends its residual waste through a central sorting facility, thereby separating plastic, metal and paper from residual waste. This practice is considered to help Norway reaching the circular economy targets and multiple sorting facilities are currently in the planning phase.

Improving organic collection was found to be the key factor leading to a higher recycling rate. Better organic collection will also increase the performance of the sorting facility which leads to more plastic recycling and secures a high climate benefit. To reach the municipal recycling target, it is necessary to improve the collection of all waste fractions. Implementing multiple sorting facilities is not enough to reach the 65% target, but is considered as an effective strategy to reach the 55% target. However, the benefits from a sorting facility are likely to be dependent on the performance of each waste management system.

Abbreviations

RoAF	Romerike avfallsforedling
RUL	recycling, utilization and landfilling
GHG	greenhouse gas
AD	anaerobic digestion
LCA	life cycle analysis
MFA	material flow analysis
EU	European union
MSW	municipal solid waste
ISWN	integrated solid waste management
SWM	solid waste management
RW	residual waste
P&C	paper and cardboard
GB	green bags
G&M	glass and metal
GWP	global warming potential
LHV	lower heating value

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1 Introduction

Development practices in the 20th century have led to challenges such as climate change, resource depletion and a need for a de-carbonized energy supply (Rogner et al., 2007). De-coupling economic development from increased resource consumption is considered as a necessity for future development. This should enable countries to industrialize on a sustainable way and increase the quality of life for many. Hence, the current linear economy should be transformed into a circular variant where most finite resources are captured and reused. To secure a closed loop of resources, the waste sector is crucial. Excellent waste management enables the sector to face all the three challenges mentioned earlier; increased recycling counters resource depletion, energy recovery of waste products supports a transition on the energy level and together, they combat climate change by reducing greenhouse gas emissions.

The European Union has recognized this and adopted the circular economy package in 2015. The package describes ambitious recycling goals for its member states. Forcing the waste sector to find solutions that are environmentally effective, economically affordable and socially acceptable. However due to the interconnectivity of the challenges and the increased complexity of waste systems, decision makers find it difficult to find comprehensive solutions. This has led to the following research question:

“How will inter-communal waste companies achieve EUs targets for a circular economy on a sustainable way?”

Pires et al. (2011) assessed the use of different models in municipal solid waste management and identified a lack of appropriate system analysis methodologies in the EU. A lack of articles studying waste systems in Norway shows that models and tools are needed to rationalize Norway’s waste management choices (Pires et al., 2011).

In this context, a generic model for municipal solid waste management has been developed. The model is built upon the principles of material flow analysis, a fundamental tool in industrial ecology, and meets the flexibility requirements necessary to take local constraints into account. This facilitates the analysis of a specific value chain to identify key factors influencing circularity. Based on different management actions, scenarios can be developed to design a pathway towards higher recycling rates and lower emissions. Hereby supporting decision making in intercommunal waste companies.

The model has been applied on the urban waste management system of Romerike Avfallsforedling (RoAF) outside Oslo. RoAF adopted the goals of the circular economy package internally, and strives to accomplish a recycling rate of 70% by 2030. RoAF is currently the only company that sends its residual waste through a central sorting facility, thereby separating plastic, metal and paper from residual waste. This practice is considered to help Norway reaching the circular economy targets and multiple sorting facilities are currently in the planning phase.

2 Literature review

2.1 Introduction to waste engineering

A waste management system is generally divided in four phases (Christensen, 2011): (1) waste generation, (2) collection and transport, (3) treatment and (4) recycling, utilization and landfilling (RUL). Based on the number of inhabitants it services, a waste management system can significantly differ in size and complexity. The separate phases are interconnected and measures taken in one phase are likely to influence downstream phases. It is therefore beneficial to maintain a holistic perspective while analysing a waste management system.

Waste generation is the first phase and aims at gathering proper information about the waste being generated. Waste can be divided in various categories (for example residential waste, industrial waste, commercial waste, etc.), types (for example garden waste, bulky waste, household waste, etc.) and fractions (paper, glass, organic waste, etc.). The waste quantities are defined in weight or in volume. The generation rate is a key parameter and is often defined per time frame (Christensen, 2011). For example, kg/year/person.

The second phase focuses on the waste storage at source and the collection/transport to the treatment and RUL facility. The in-house collection, mainly represented by bins and bags, serves as a buffer between the actual generation and the collection of the waste. Waste is mostly segregated in several types or fractions to match the collection system. During the collection, a vehicle collects waste at the pick-up location and transports it to where it will be unloaded.

When the waste is transported to the treatment facility it will be treated thermally, mechanically or biologically to recover recyclables, extract energy or improve characteristics before further handling (Christensen, 2011). Thereafter, the waste can be recycled, landfilled or utilized. When recycled, the original materials characteristics are used in the production of the same or related products such as recycled glass, paper, etc. When the materials are utilized instead of recycled, mainly secondary characteristics are being used. Utilization can refer to (1) material utilization such as the use of compost as fertilizer and (2) energy utilization such as use of refuse derived fuel (RDF) used for energy purposes. Finally, when landfilling, land is used to bury the waste that was generated.

2.2 Greenhouse gas emissions

In 2014, the waste management sector accounted for 3.3% of the total greenhouse gas (GHG) emissions emitted in the EU-28 (Eurostat, 2016). Methane (CH_4) is the largest single contributor to the emissions in the waste sector, followed by nitrous oxide (N_2O) and carbon dioxide (CO_2) (Bogner et al., 2007). Although emissions happen at all stages of the waste value chain, it is common to only account the emissions from the direct waste management processes, such as landfilling or waste incineration, to the waste sector. Emissions from other waste treatment activities are included in other sectors such as transport and industrial processes. The overall emissions related to waste management are thus likely to be slightly higher than the 3.3% presented above.

If managed properly, the waste sector can have negative GHG emissions (Skovgaard, Hedal, & Villanueva, 2008). Secondary raw materials are used to produce new products, thereby replacing primary raw materials and its emissions. When waste cannot be recycled, its energy can be recovered and used to generate heat and power. When the avoided emissions are accounted to the waste sector, they can offset the generated emissions and "create" negative emissions. Effective waste management can therefore help to decrease overall emissions and contribute to the decoupling of emissions and economic growth.

2.2.1 Collection

According to Skovgaard et al. (2008), the collection and transport of waste is only a small contributor to the climate change effect of the waste sector. Based on a projection of the GHG emissions for the EU-27 from 1980 to 2020, Skovgaard et al. (2008) conclude that the collection and transport of waste accounts for less than 5% of the estimated emissions. The decision of which collection system will be used is thus mainly based on technical, social and financial criteria without analysing the environmental impacts (Calabrò, 2009).

Iriarte, Gabarrell, & Rieradevall (2009) analysed therefore the environmental impact of three selective collection methods in an urban area: pneumatic, door-to-door and multi-container systems. The pneumatic system has the greatest environmental impact related to among others global warming potential, fresh water- and terrestrial ecotoxicity, acidification and eutrophication. The total energy demand is also found to be 28% higher than the average demand of other systems (Iriarte et al., 2009). The door-to-door system has the highest impact on human toxicity and ozone depletion and the multi container system has generally the lowest environmental impact.

To analyse the real environmental impact from a collection decision, recycling processes should be included into the system boundary. Calabrò (2009) concludes that separate collection, resulting in more recycling, can have a significant positive effect on the reduction of overall GHG emissions. It is therefore important to compare higher emissions caused by separate collection with the increase in recycled material/recovered energy and its avoided emissions.

2.2.2 Treatment

Landfills are considered having the biggest environmental impact in the waste sector (UNEP, 2010). In 2005, methane emissions from waste disposal sites in the EU-15 accounted for 75% of the total GHG emissions of the sector (Skovgaard et al., 2008). When residual waste is deposed in a landfill, it contains a large part of organic material. Under anaerobic conditions, the organic matter degrades resulting in the formation CH_4 and CO_2. Most of the landfill gas is released to the atmosphere within 30 years after deposing (Jahren, 2016). Other fractions such as plastic, glass and metal generate less emissions when landfilled because of their less reactive or inert behaviour.

Thermal treatment of waste (such as-mass incineration) generates mainly CO_2 emissions. Both fossil and biogenic CO_2 emissions are emitted due to the composition of the waste that is being treated. The incineration of organic material such as wood or food waste, generates biogenic emissions and is therefore considered neutral towards climate change. Other products such as plastic result in fossil CO_2 emissions. The amount of fossil carbon in the input waste is therefore the main factor influencing GHG emissions from incineration (Astrup, Møller, & Fruergaard, 2009). In addition, indirect emissions from the energy consumed by the incineration plant can significantly influence its environmental footprint. However, this depends heavily on the used energy mix (Astrup et al., 2009).

Recycling waste is a complex process, involving different processes which all consume various amounts of energy. As recycling will increase over time, these activities will represent a significant fraction of the total GHG emissions in the waste sector (Skovgaard et al., 2008). Depending on the type of waste being recycled, the energy consumption can have a significant impact on the overall emissions. For the recycling of paper and cardboard, the energy mix used in the recycling process is considered as a key factor influencing the environmental footprint of recycled paper (Michaud, Farrant, Jan, Kjær, & Bakas, 2010).

Composting and aerobic processes emit various levels of CH_4 and N_4O, depending on how the process is managed (UNEP, 2010). Closed systems usually emit less because they can treat the air exiting the facility. Energy requirements from composting plants are small, hence low indirect upstream emissions are expected. Anaerobic digestion (AD) systems are less likely to have system leaks because the digestions happens in closed tanks (UNEP, 2010). Emissions are thus mainly caused by the higher energy requirement. However, most facilities use a share of their biogas in-plant which significantly reduces the upstream emissions (UNEP, 2010).

2.2.3 GHG savings

Avoided emissions are a key factor in waste management. The term is mostly used in Life Cycle Analysis (LCA) studies comparing landfilling, incineration and recycling as different waste treatment options. Avoided emissions compensate increased recycling emissions, making recycling the most beneficial option for paper and cardboard, plastics and metals (Michaud et al., 2010). However, local conditions can have a substantial impact on the benefits of each recycling process.

For paper and carboard, the energy mix used during the recycling process and the replaced energy mix due to the incineration process are crucial factors (Michaud et al., 2010). If a high carbon mix is replaced, incineration might be to most beneficial option. However, as most developed countries are evolving to a low carbon energy mix, recycling of paper and carboard will become increasingly favourable over energy recovery (Michaud et al., 2010).

Recycled plastic requires significantly less energy to produce, hence it generates a high amount of avoided emissions (Christensen, 2011). The environmental benefits even increase when clean and high quality plastics are collected (Michaud et al., 2010). An important factor to consider is the substitution ratio of virgin plastic by recycled plastic (Michaud et al., 2010). A substitution rate of 20% does not generate enough avoided emissions to compensate for recycling emissions, resulting in a net contribution to emissions. Landfilling plastic does not generate any avoided emissions because of its slow degradation process and is therefore considered as the least beneficial option.

Recycling metal requires significantly less energy than the production of virgin metals (Raadal, Modahl, & Lyng, 2009). The generation of avoided emissions are therefore quite certain (Christensen, 2011). Metals are furthermore inert in landfills and have no major function in incineration plants, making those options not attractive.

Besides incineration, organic waste can be composted or threated anaerobically. The former option generates avoided emissions by the substitution of peat or other fertilizers. Some studies point out that even the increased carbon storage in soils trough compost utilisation could already be enough to generate a net reduction in GHG emissions (Michaud et al., 2010). The latter option generates energy which can, just like the incineration of organic waste, replace other fossil energy sources. The electricity mix is therefore again a key parameter (Michaud et al., 2010). Replacing a low carbon energy mix by incinerating organic matter generates few or no avoided emissions. In addition, when biogas replaces the use of fossil fuels, the benefits are clearly in favour of recycling (Michaud et al., 2010).

2.3 Circular economy

In a circular economy, industrial systems behave like ecosystems; "recognizing the efficiency of resource cycling in the natural environment" (Preston, 2012). The current economic system is linear. Natural resources are extracted, turned into products and finally discarded. This puts pressure on finite resources that should power infinite growth. In a circular economy, one aims at closing the loop. Meaning that large volumes of finite resources are captured and reused. By de-linking economic development from increased resource consumption, countries can industrialize on a sustainable way.

A circular economy also offers opportunities for increased competitiveness. Business models will have to be redesigned to fit the circular framework, providing first mover advantages (Preston, 2012). In times of increased resource price volatility, constant prices for recycled resources can further power business growth and turn out to be a strategic weapon against increased global competition (Preston, 2012).

2.3.1 Europe

The European Union (EU) recognized the need for a circular economy and has therefore taken multiple actions to accomplish this goal. In 2008, the EU adopted the Waste Framework Directive (European Commission, 2008). This directive explains the concepts and definitions related to waste management and introduces basic principles such as the waste management hierarchy, the polluter pays principle and extended producer responsibility. In 2015, the Waste Framework Directive was amended (European Commission, 2015b) and it is now an important part of the Circular Economy Package adopted by the European Commission in 2015.

The Circular Economy Package contains different recommendations, rules and goals for its member states. The main goal of the package is that "by 2030, the preparing for re-use and the recycling of municipal waste shall be increased to a minimum of 65% by weight" (European Commission, 2015b). Intermediate goals for 2020 and 2025 are set at 50% and 60% respectively. In addition, Article 22 of the directive recommends the separate collection of bio-waste to attain the goals presented above. "The member states shall take measures to encourage the recycling, including composting, and digestion of bio-waste" (European Commission, 2015b). In 2015, the commission proposed to amend multiple directives in the circular economy package. A proposal was submitted to change Article 6 of Directive 94/62/EC on packaging and packaging waste. If the proposal will be adopted, 55% of plastic packaging waste should be prepared for reuse and recycling by 2025 (European Commission, 2015a).

Decision 2011/753/EU of the European commission presents the different calculation methods that can be used to ensure an effective implementation of the targets presented earlier (European Commission, 2011). Article 3 of the decision presents the possible scopes on which the member states can apply the targets: (1) "the preparation for reuse and the recycling of paper, metal, plastic and glass household waste" (2) "the preparation for reuse and the recycling of paper, metal, plastic, glass household waste and other single types of household waste or of similar waste from other origins" (3) "the preparation for reuse and the recycling of household waste" and finally (4) "the preparation for reuse and the recycling of municipal waste" (European Commission, 2011). Another crucial element in the decision is that "the input to the aerobic or anaerobic treatment may be counted as recycled where that treatment generated compost or digestate which, following any further necessary reprocessing, is used as a recycled product, material or substance for land treatment resulting in benefit to agriculture or ecological improvement" (European Commission, 2011).

To monitor progress in the implementation of directive 2008/98/EC, member states must deliver an implementation report every three years. The implementation report is drawn up on the basis of a questionnaire and the first report was due in December 2014 (European Commission, 2008). Member states shall also report data to the commission showing their results concerning the circular economy targets. The first report shall cover data for the period form 1 January 2020 to 31 December 2020 and is due 18 months after the end of this period (European Commission, 2015b). In addition, member states are encouraged to establish waste management plans containing "an analysis of the current waste management situation as well as the measures taken to improve environmentally sound preparing for re-use, recycling, recovery and disposal of waste" (European Commission, 2008).

2.3.2 Norway

In the latest implementation report, Norway describes the implementation of directive 2008/98/EC. First, the directive has been transposed into the national law ("Waste Framework Implementation Report," 2016), hence providing a legal basis for the directive. Second, a national waste management plan has been developed. The plan presents a waste strategy focussing on waste prevention, increased material recycling and environmentally sound treatment of hazardous waste in multiple sectors (Miljøverndepartementet, 2013). Finally, Norway suggests to calculate the material recycling rate based on "the preparation for reuse and the recycling of household waste" ("Waste Framework Implementation Report," 2016). This results in a material recycling rate of 39,2% in 2013, 37,4% in 2014 and 37,9% in 2015 ("Waste Framework Implementation Report," 2016). Those recycling rates are still lower than the 2020 targets and significantly lower than the targets for 2030.

As a part of the national (bio) waste strategy, the national environmental agency considers means for higher material recycling of organic waste and plastic waste. According to the agency, the most effective means to do this is to enforce the separate collection of organic waste and different types of plastic (Miljødirektoratet, 2017a). To ensure that better sorting leads to more recycling, a certain level of material recycling should be enforced (Miljødirektoratet, 2017b). Organic waste has a high density and represents therefore over a third of the total residual waste generated in Norway (Miljødirektoratet, 2017b). Increased recycling of this fraction will thus significantly contribute to accomplishing the EUs targets.

Introducing separate collection of organic waste for those who do not have this (30% of the population), will increase the collection efficiency for organic waste to 64% by 2020 (Miljødirektoratet, 2017b). Improving and expanding those practices to the private sector by 2030 is assumed to result in a collection efficiency of 80% (Miljødirektoratet, 2017b). The agency advises to separate organic and residual waste before entering a central sorting facility. This ensures good sorting by the central sorting facility (Miljødirektoratet, 2017b). Together with increasing the biological treatment capacity to 150.000 tonnes by 2030, this should be sufficient to meet the European targets by 2030 (Miljødirektoratet, 2017b).

To increase material recycling, plastic should be separated from residual waste at the source or by a central sorting facility (Miljødirektoratet, 2017b). Currently only one central sorting facility is operational and three are in the planning phase. When all four facilities are operational by 2020, potentially 25.000 extra tonnes of plastic are send to recycling (Miljødirektoratet, 2017b). Introducing separate collection of plastics for those areas that are not covered by one of the planned central sorting facilities, as well as including the private and agricultural sector should increase plastic recycling from 39% to 45% by 2020 (Miljødirektoratet, 2017b). Replacing separate household collection by ten sorting facilities in the long run, activates the potential for 110.000 extra tonnes of plastic being sent to recycling (Miljødirektoratet, 2017b). Combining all those actions should result in a material recycling rate of 60% by 2025 and 65% by 2030 (Miljødirektoratet, 2017b).

2.4 System analysis in waste management

2.4.1 Development

In the 1970s, models in waste management had a rather narrow scope. Aiming to solve specific problems such as optimizing collection routes or the placement of a transfer station (Morrissey & Browne, 2004). Given the specific type of the problems being modelled, programming techniques were most popular. The early models had a shortcoming of being static, meaning that they only studied the specific problem for a given time. According to Sudhir et al. (1996), this made them unsuitable for long term planning.

In the 1980s, the perspectives were enlarged and the system boundaries were extended. Instead of studying a single problem, relationships between different factor were now being analysed

(MacDonald, 1996). The main focus was economical, aimed at minimizing costs in Municipal Solid Waste (MSW) management (Gottinger, 1988).

In the 1990s, recycling received more attention and found its way into the models. Furthermore, policy and technology changes were more commonly included in holistic models. This pushed the field more to the principle of Integrated Solid Waste Management (ISWM). “ISWM considers the full range of waste streams to be managed and views the available waste management practices as a menu of options from which to select the preferred option based on site specific environmental and economic considerations” (Morrissey & Browne, 2004). Recent models stress sustainability by taking a more life cycle approach.

2.4.2 Models in solid waste management

As touched upon in previous sections, Solid Waste Management (SWM) systems are highly interconnected and many actors are involved. Chang et al. (2011) described a SWM system as a complex “system of systems”. Subsystems such as landfills and incinerators are linked with each other through processed waste streams, providing varying functionality and performance. This complexity may result in local outcomes not being aligned with global outcomes. To fulfil the needs of waste management and preserve natural ecosystems at the same time, connections should be mapped and assessed carefully.

System models can help the waste sector to make environmentally sound decisions that will contribute to sustainable development. To meet the demands of future generations, current SWM systems should be managed from a sustainable perspective (Chang et al., 2011). System models and assessment tools connecting all waste, resources and energy flows together will therefore become a necessity in the 21st century (Chang et al., 2011). Furthermore, every community has its own constraints meaning that a solution should be tailored to meet local requirements, adding complexity to the system but making generic models highly attractive (Najm et al., 2002).

Morrissey & Browne (2004) concluded that SWM models should be “environmentally effective, economically affordable and socially acceptable”. In this context several models have been developed. Hung et al. (2007) proposed a Consensus Analysis Model (CAM) to incorporate public participation in SWM decision making. This would “avoid high levels of controversy and public opposition that have surrounded many MSW projects” (Wilson et al., 2001). Chifari et al. (2016) started from a metabolism theory rooted in ecology to quantify the technical and economic outputs of a waste system on the metropolitan area of Naples, Italy. Chertow & Eckelman (2009) used Material Flow analysis to evaluate long term waste management solution on the Island Oahu, Hawaii. Import, export, consumption and substitution scenarios were analysed to streamline the generation of waste with local conservation, recycling and economic goals.

In slight contrast to the models presented above, Shmelev et al. (2006) concluded that most models lack a holistic view over the SWM system. Methods such as Life Cycle Assessment, which have been increasingly popular the last decade, tend to focus on a single problem and could provide the decision maker with too narrow perspective. Driven by the increased complexity of waste systems and the lack of a holistic view, Chang et al. (2011) concluded that "sound modelling techniques for solving regional SWM problems in an all-inclusive approach are missing".

2.4.3 Classification and Evaluation

MSW models can be classified based on two domains; system engineering and system assessment tools (Chang et al., 2011). System engineering models include cost-benefit analysis (CBA), forecasting model (FM), simulation model (SM), optimization model (OM) and integrated modelling system (IMS). System assessment tools are represented by management information systems (MIS), decision support systems (DSS), expert systems (ES) and by tool such as: scenario development (SD), material flow analysis (MFA), life cycle assessment/inventory (LCA/LCI), risk assessment (RA), environmental impact assessment (EIA), strategic environmental assessment (SEA), socioeconomic assessment (SoEA) and sustainable assessment (SA).

Figure 1 illustrates the interrelationships between the two main domains. System engineering models can be found in the central part and CBA is often used as a platform for decision making. Optimization models such as mixed-integer (IP), (non) linear (NLP/LP) and dynamic

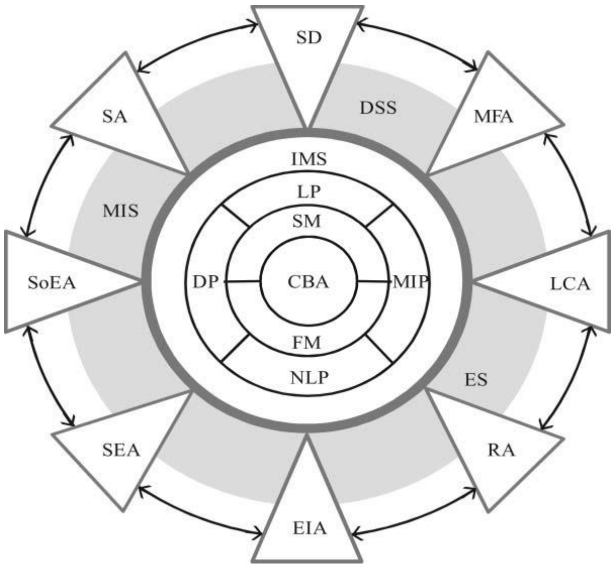


Figure 1: The technology hub for solid waste management analysis (Chang et al., 2011).

programming models (DP) can be used to provide the fundaments for SM and FM models, supporting the cost benefit analysis. All core models can be supported by the system assessment tools illustrated by the eight outer triangles. Supported by the recent realization that LCA should not exist in absence of other tools (Kijak & Moy, 2004), Pires et al. (2011) pointed out that SWM actors may be able to get over the complexity of the systems due to the synergic effects between the two domains.

System assessment models have been most popular in Europe (Figure 2). This can be explained by theoretical character of system engineering models. Due to the large amount of assumptions that have to be made, they are not easy to implement and might be considered as less realistic (Pires et al., 2011). However, when coupled with a system assessment model, some of these drawbacks can be limited. Making them very powerful tools which can help decision makers to learn about the system complexity (Pires et al., 2011).

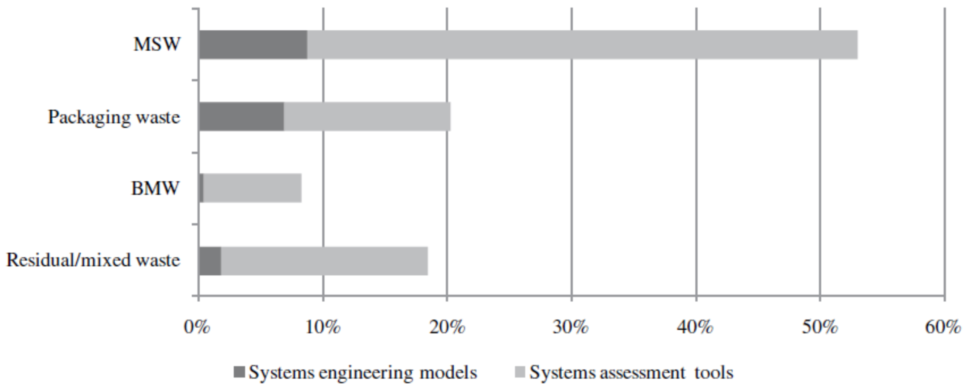


Figure 2: System analysis applied in SWM systems in Europe (Pires et al., 2011)

To evaluate different scenarios, simple but comprehensive Key Performance Indicators (KPI) are necessary. KPIs should be calculated by local administrations and managers of waste systems and not by experts only (Rigamonti et al., 2016). Different indicators have been introduced in the field. The Resource Conservation Efficiency (RCE) proposed by Kaufman et al. (2010) considers the energy produced and the material sent to recycling in one metric. Vivanco et al. (2012) developed a Net Recovery Index (NRI) similarly to the RCE but focussed on organic waste. Rigamonti et al. (2016) concludes that most indicators evaluate individual components and not the entire integrated waste management system. Therefore, the Material Recovery Indicator (MRI), the Energy Recovery Indicator (ERI) and the Cost Indicator (CI) are proposed to compare different integrated MSW management systems in an objective way (Rigamonti et al., 2016).

3 Case study description

3.1 RoAF

Romerike Avfallsforedling (RoAF) is an inter-communal waste company outside Oslo. It is owned by Aurskog-Høland, Enebakk, Fet, Gjerdrum, Lørenskog, Nittedal, Rælingen, Skedsmo and Sørum. Besides those nine municipalities, RoAF also manages waste from Rømskog, all together serving over 195.000 inhabitants. Inspired by the circular economy package, RoAF strives for a 70 % recycling rate by 2030. To meet this goal, RoAF is active on various levels of the waste pyramid (Figure 3).

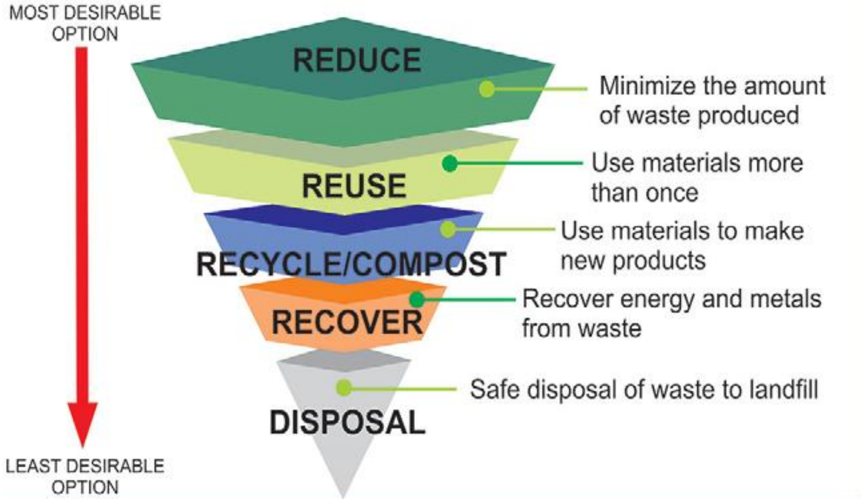


Figure 3: Waste pyramid showing the priorities in waste management (Brattebø, 2016)

To reduce the amount of waste, RoAF supports the usage of cloth diapers. A shift from disposable to cloth diapers has the potential to reduce the amount of generated waste with 2000 tonnes (RoAF, 2016). Children from the local schools are also invited to RoAF to learn about waste and recycling. This ensures long-term commitment from the inhabitants to the recycling targets. To increase the amount of reused goods, RoAF is collaborating with local organisations and opening more second-hand stores at their recycling stations. This gives households the opportunity to give products a second life instead of discarding it. Especially clothes are discarded in the residual waste bin, thereby creating several problems downstream. To capture this valuable resource, RoAF collaborates with Fretex and UFF.

To divert waste from incineration to recycling, RoAF installed a high-tech central sorting facility next to its offices in Skedsmo. All residual waste collected at households is sent through the facility and recyclable materials such as plastic, paper and metal are separated from the original waste flow. To improve the sorting from diverse types of plastic, RoAF is collaborating with food concerns such as Orkla to change the composition and colour of plastic packaging.

In 2016, RoAF reported a material recycling rate of 45.4% and an energy recovery rate of 53.3% for its household and business clients together. 1.2% of the generated waste was reused and 0.1% was landfilled (RoAF, 2016). Compared with 2015, material recycling has increased with almost 5 percentage-points (pp). The shift from incineration towards a 70% recycling rate has therefore been initiated.

3.2 Waste generation and segregation

RoAF has two bins at each household, one for residual waste (RW) and one for paper and cardboard (P&C). Organic waste is gathered in green bags (GB) which are discarded in the RW bin. Normal containers are used to serve multiple households at once, but most of them are to be replaced by their underground version or by vacuum systems. These collection methods are believed to generate a cleaner waste stream. Underground containers are mostly installed in group, with one container for each waste type. The proximity of the different bins makes households less inclined to throw their waste in the wrong bin.

Glass and metal (G&M) is currently brought to collection points spread over RoAF's area. In one area (Aurskog-Høland and Rømskog), RoAF introduced a separate bin for G&M at each household. Other areas will follow, which means that RoAF is evolving to a three-bin system. Hazardous and electronic equipment is collected twice a year or can be brought to one of the eight recycling stations. Other waste types should be brought to the recycling stations.

In 2016, 54% of the household waste is collected and 46% is delivered to the recycling stations. From the collected waste, 43% is material recycled whereas 57% is incinerated. For the recycling stations, 47% is recycled, 49% is incinerated and 3% is reused (RoAF, 2016). Based on this, it was decided to leave waste delivered to recycling stations out of the analysis. When delivered to one of the parks, waste is sorted with the help of supervisors. Sorting errors and the potential for higher recycling rates is therefore considered to be lower than with collected household waste. The four types of waste included in the study are therefore G&M, P&C, RW and GB containing organic waste. Together they represent eight waste fractions: glass, metal, plastic, organic waste, paper & cardboard, hazardous waste, textiles and residual waste.

3.3 Collection and transport

RoAF's responsibility for managing waste is geographically divided in four areas. Each of those areas have a different subcontractor responsible for the collection of RW and P&C. In three of the four areas, RoAF itself is responsible for emptying the underground containers and the mobile vacuum system. It has therefore three vehicles, two vehicles serving the underground containers and one emptying the mobile vacuuming system. In some areas, every vehicle is powered with biogas whereas in other areas none (appendix A.3a). Across all the subcontractors and RoAF, nine diesel cars and 12 biogas cars are used to collect RW and P&C. G&M is collected by only one subcontractor for all the areas and all their cars are diesel fuelled.

Most of the RW is transported directly to the central sorting facility at Skedsmo. Only the RW from Aurskog-Høland and Rømskog is transported to the transfer station at Spillhaug (in Aurskog-Høland) and then transferred to the central sorting facility. P&C collected at households and recycling parks is transported directly to Ragn Sell's treatment facility in Lørenskog. Similarly, G&M from collection points and parks is gathered at Skedsmo where it is reloaded and transported to the Syklus's sorting facility in Fredrikstad.

3.4 Treatment and RUL

RW, including GB is sent through the central sorting facility at Skedsmo. Subjected to various treatment technologies, the following waste fractions are separated from the input waste flow: plastic (PET, PP, PE, foils and mixed plastic), paper, metal (magnetic and non-magnetic) and GB with organic waste. P&C collected from the households is sorted at Lørenskog and then sent to different paper and board factories across Norway and Europe. When arrived at those recycling facilities, a second sorting process is undertaken to separate more difficult parts from each other. G&M is separated from residual fractions and sorted based on colour and type in the facility in Fredrikstad.

The organic waste that has been sorted is delivered to a biogas plant in Hadeland (HRA). Biogas is produced as the main product and used as fuel for collection vehicles. The by-product residual sludge is used as fertilizer. The plastic from the sorting plant is sent to different recycling facilities in Norway, Sweden and Germany. When metal and aluminium are sorted at Skedsmo and Fredrikstad, it is sent to melting facilities across Norway and Sweden. Some glass will be used as raw material for isolation whereas other types will be exported to different glass production plants in Europe.

The rest fractions from the different treatment facilities are incinerated in the facility at Klemetsrud or in different facilities across Europe. The energy is recovered and can be utilized as heat and power. The ashes from Klemetsrud are sent to a bottom ash treatment facility from Nork Gjenvinning and valuable metals are recovered. The residual ashes are landfilled.

4 Method

4.1 Material Flow Analysis

Material flow analysis (MFA) is a systematic assessment of the flows and stocks of materials within a system, defined in space and time (Brunner & Rechberger, 2004). It connects the sources, pathways, and the intermediate and final sinks in a material management system. Based on the law of conservation of matter, the results of a MFA can be obtained and controlled by a simple material balance which compares all inputs, stocks and outputs of a process or a system (Brunner & Rechberger, 2004). MFA enables the analysis of product consumption patterns, waste generation, recycling, recovery and reuse, thereby leaving the traditional boundary of SWM (Brunner & Rechberger, 2004). It is this distinct characteristic that makes MFA an attractive method for decision support in resource, waste and environmental management.

Figure 4 shows the different steps in the process of conducting an MFA. First, the problem is defined and objectives for the analysis are formulated. Secondly, the system is defined by selecting system boundaries, processes and flows. Once the relevant flows are selected, the mass flows are quantified. Finally, the stocks are calculated and uncertainties are evaluated.

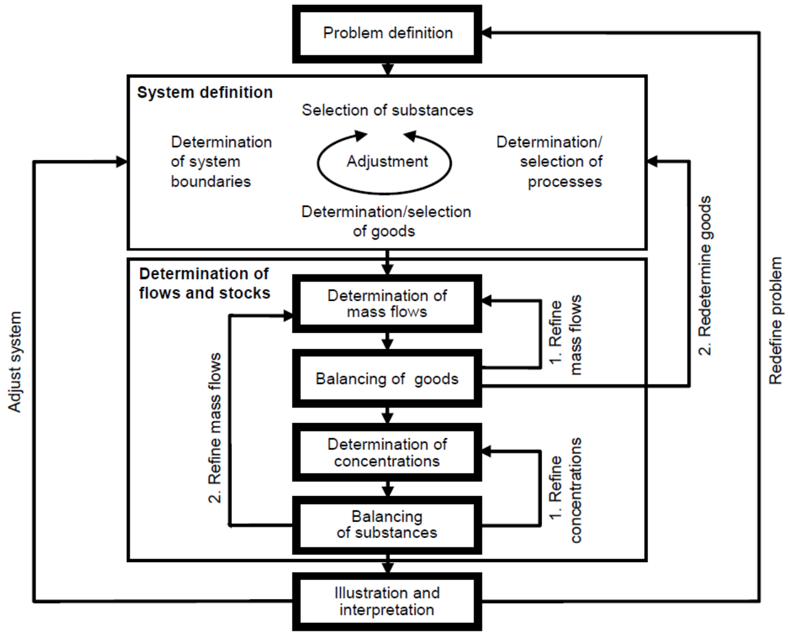


Figure 4: Iterative process for MFA (Brunner & Rechberger, 2004)

One should note that this is an iterative process, meaning that one should start from a simple version and build towards the final purpose of the model. In this context, it is best to start with rough estimations of data and then gradually refine and update the system (Brunner & Rechberger, 2004).

The MFA principles presented above have been applied on RoAF's system to develop a generic representation of a municipal waste management system. The model can therefore serve as a starting point for mapping other municipal waste systems. By iteration, processes, flows and stocks can be re-evaluated to obtain the correct representation of a specific municipal waste system.

The model (Figure 5) represents the waste flows and processes necessary to treat waste, from when it is generated to when it is sold to an external market. The system boundary is therefore the entire municipal waste system. The representation contains 12 processes and five external markets where the former waste products start a new value chain. Similarly to the four phases defined by Christensen (2011), the 12 processes can be divided in three groups. The collection processes (process 1, 3, 5) represent the different methods on how waste can be collected: at households, by collection points or at recycling parks. The sorting processes (process 2, 4, 6,

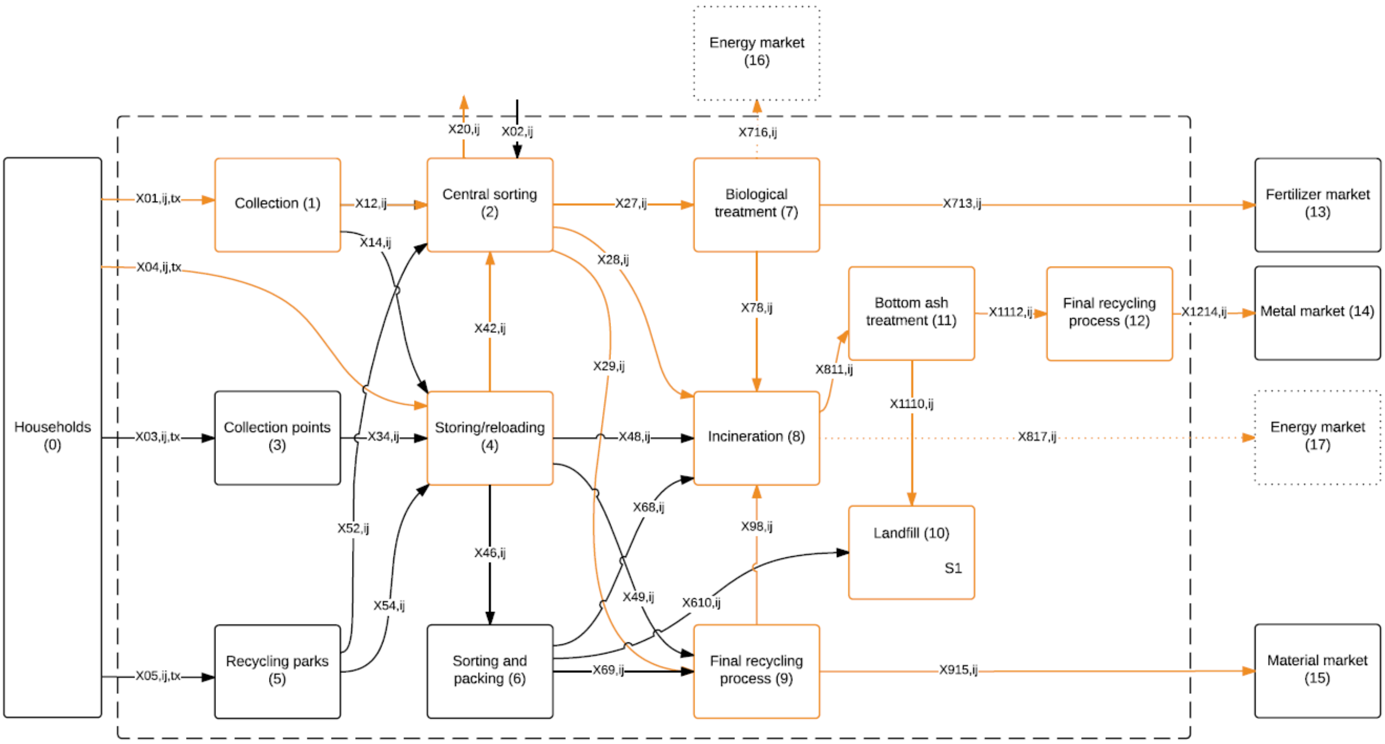


Figure 5: Generic municipal waste system.
The active flows and processes for RW in the case of RoAF are given in orange.
The flow chart for P&C and G&M are given in appendix A.1

11) separate the waste flow in different fractions. They exist of a central sorting process, two sorting/reloading/packing processes and one bottom ash treatment process. The treatment processes (process 7, 8, 9, 10, 12) represent the final phase of waste management where the materials are recycled, utilized or landfilled.

4.2 Model

The interconnectivity of the waste sector demands an evaluation based on various levels. Because the fundaments of this analysis are based on a MFA, the first level maps the material flows. The second level represents the role of waste management in the energy sector based on the material flows in the first level. The third level calculates both the generated and avoided emissions from the first and second level, to quantify the impact on the environment.

4.2.1 Material

The material layer requires the input of waste flows and transfer coefficients. The waste flows are written by $X_{ab,ij,}t_x$ (Table 1) and represent the waste that is collected or transported. In accordance with the four waste types and eight fractions defined in section 3.2, this means that each flow X_{ab} represents 32 waste flows. Transfer coefficients ($T_{ab,ij}$) represent the specific technology of a process. They determine the share of the total inflow from process a that goes to process b.

Comment	Symbol	Possible Unit
Transfer coefficient from process a to b	T_{ab}	%
Waste flow from process a to b	X_{ab}	ton/yr, kg/cap
Waste type i	i	ton/yr, kg/cap
Fraction j of waste type i	ij	%, ton/yr, kg/cap
Collection technology x	t_x	%, ton/yr, kg/cap

Table 1: Explanation of symbols used in Figure 5

To deal with this level of complexity without compromising the flexibility of the model, the model was written in MATLAB. Based on the flows and processes defined in Excel, MATLAB reads the given waste flows and transfer coefficients from Excel (appendix A.2a). These flows and coefficients are then used to calculate the missing flows, considering the principle of conservation of matter. The data used to quantify the fractions of each waste flow is based on a sample analysis carried out by Mepex consult (appendix A.2a).

Waste can be collected using different collection technologies (t_x). As mentioned briefly in section 3.2, RoAF uses small bins, underground bins, containers, mobile vacuuming systems and a stationary vacuuming system. These technologies are likely to generate different waste compositions. Waste companies are therefore increasingly interested in adjusting the collection technology mix to improve the purity of the collected waste. To include this in the model, collection flows can be specified for each collection technology. This enables the user to study the impact of a shift in collection technology. However, due to a lack of representative sample analyses, no difference in waste composition is assumed for the collection technologies in this study. Underground bins, containers and vacuuming systems will therefore generate the same level of purity of a specific waste type.

RoAF is currently the only actor in Norway that has a central sorting facility, hence transfer coefficients were not available and had to be calculated. Sample studies from the inflow of the machine combined with data on the outflow gives the specific transfer coefficient for each fraction (Table 2). Related to the GB flow, 72% of the organic waste entering the machine is sorted and sent to biologic treatment (T27), the remaining amount follows the residual waste stream and is therefore incinerated (T28). This is in line with Syversen & Bjørnerud (2015) who concluded that the amount of green bags exiting the facility is 30% and 22% lower than the amount entering it for 2014 and 2015 respectively. The bags are mostly damaged due to transport and treatment processes which leads to high losses of organic waste and increased difficulties in the sorting process.

	GB		RW		
Fraction	T27	T28	T27	T28	T29
Glass	0%	0%	0%	100%	0%
Metal	0%	0%	0%	12%	88%
Plastic	0%	0%	0%	64%	36%
Organic	72%	28%	0%	97%	2%
P&C	0%	0%	0%	59%	41%
Residual	0%	0%	2%	98%	0%
Hazardous	0%	0%	0%	100%	0%
Textiles	0%	0%	0%	100%	0%

Table 2: Transfer coefficients of the central sorting facility. Calculations are presented in appendix A.2b

For the RW flow, a high sorting efficiency for metal can be observed (88%) unlike the sorting of P&C (41%). Remarkable is also that only 36% of the incoming plastics have been sorted. RoAF points out that this is mainly due to organic waste which makes plastic dirty and difficult to be recognized by different sorting technologies. In addition to the losses of the green bags in the sorting process, only 48% of all the organic waste is collected in the green bags (Syversen & Bjørnerud, 2016). This results in a high amount of loose organic waste in the RW bin, hence dirtying the plastics. Other fractions such as glass, hazardous materials and textiles follow the residual waste flow towards the incineration plant (T28). Also 2% of the residual waste fraction follow the GB towards the biological treatment facility.

From the two datasets that are necessary to calculate the transfer coefficients of the central sorting facility, the inflow data is the most uncertain. The areas from which the waste composition were analysed are specifically chosen to be representative for RoAFs total area (Syversen & Bjørnerud, 2016). However, the variance between those areas has a significant impact on the coefficients calculated before. When the transfer coefficients are calculated based on the extremes of the 95% confidence interval (Table 3), one can observe that the transfer coefficient for metal is rather uncertain compared with plastics and paper.

	Max	Average	Min
Metal	98%	88%	81%
Plastic	38%	36%	34%
P&C	45%	41%	38%

Table 3: Uncertainty in the central sorting TC
Possible values for T29 based on the max and min values of the 95% confidence interval of the sample analysis by (Syversen & Bjørnerud, 2016)

To evaluate the performance of the material layer, three indicators are chosen. The collection efficiency evaluates the performance of the waste collection system and is defined as "the amount of waste collected correctly over the total amount of household waste generated" (Equation 1). A high collection efficiency leads to pure waste streams. As residual waste is usually collected in the correct bin, this fraction is not included in the calculation of the indicator.

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

Equation 1: Collection efficiency
Vector a represents all the collection processes. i in the numerator determines the correct bin for fraction j.

Sorting efficiency is defined as "the amount of waste sent to recycling after sorting over the total amount of household waste generated" (Equation 2).

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

Equation 2: Sorting efficiency
Vector b represent all the final recycling processes.

To evaluate the performance of the entire waste system related to the European targets, material efficiency is defined according to the European guidelines presented in section 2.3. This leads to "the amount of household waste recycled over the total amount of household waste generated" (Equation 3).

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

Equation 3: Recycling rate
Vector c represents the material markets, vector d the bioenergy markets

To align the material recycling with company targets, a company's specific recycling rate is calculated. This indicator assumes that the waste that is send from the waste company to downstream actors is 100% recycled. A waste company that only collects waste will thus have a higher company recycling rate than a company that also does sorting (Equation 4). The vectors used in the case study are presented in appendix A.2c.

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

Equation 4: Company specific recycling rate
Vector e representing all the processes to which the company sends its waste

4.2.2 Energy

The energy layer focuses on the energy requirements and outputs of the system. The energy requirements are given by the energy necessary to transport and treat the waste. Because waste contains energy that can be recovered by incineration or biological treatment, the calorific value of the incoming waste flow should be included.

Transport energy is based on the waste flows calculated in the material layer. Each flow ($X_{ab,i}$) is multiplied with its energy intensity ($I_{ab,i,f}$) and distance ($D_{ab,i}$) (Equation 5).

$$Transport\ energy_{ab,i,f}\ \left(\frac{Kwh}{yr}\right) = Energy\ intensity_{ab,i,f}\ \left(\frac{Kwh}{tkm}\right) * Weight_{ab,i}\left(\frac{t}{yr}\right) * Distance_{ab,i}\ (km) * S_f$$

Equation 5: Transport energy
from process a to b, for waste type i and fuel type f.

Because different fuel types (f) are separated from each other, one should multiply the fuel specific energy intensity with the weight that has been transported with this fuel type. The total weight and distance of the flow are therefore multiplied with a factor (S_f) that represents "the share of the total tkm that has been transported with fuel type f" (appendix A.3a).

Unlike the energy intensities from downstream transport (appendix A.3a), the intensities for the collection flows are calculated based on the collection routes, amount of waste transported and fuel consumed by RoAF. This enables us to include the specific energy requirement of each collection technology used by RoAF. For every collection route, the energy intensity was calculated according to Equation 6. This has been done for each fuel type (f), collection technology (t_x) and waste type (i) (appendix A.3a). The average value of these route specific energy intensities is used as the energy intensity of fuel type (f) for collection flow $X_{ab,i,}t_x$. The distance to and from the collection route is not included in the analysis.

$$Energy\ intensity_{f,t,i}\left(\frac{kwh}{tkm}\right) = \frac{Energy\ consumption_{f,t,i}\ \left(\frac{kwh}{yr}\right)}{Weight_{f,t,i}\ \left(\frac{t}{yr}\right) * route\ distance_{f,t,i}\ (km)}$$

Equation 6: Energy intensity
for a specific fuel type f, collection technology t_x and waste type i

Process energy is calculated by multiplying the incoming waste flows with the energy requirement of each process (Equation 7). The energy requirement for each process is given in appendix A.3b. The feedstock energy is obtained by multiplying the collection flows ($X_{ab,ij,}t_x$) with the Lower Heating Value (LHV) value of each fraction (appendix A.3c).

$$Process\ energy_{p,i,f}\left(\frac{kwh}{yr}\right) = Weight_{p,i}\left(\frac{t}{yr}\right) * Energy\ requirement_{p,i,f}\ \left(\frac{kwh}{t}\right)$$

Equation 7: Process energy
for process p, waste type i and energy carrier f

In the generic model (Figure 5), the energy can be recovered by incineration or biological treatment. To calculate the output of an incineration plant, the LHV of the waste inflow is multiplied with the energy efficiency of the plant (Equation 8).

$$Energy\ out_{ij}\left(\frac{kwh}{yr}\right) = \ Waste\ inflow_{ij}\left(\frac{t}{yr}\right) * LHV_i\left(\frac{kwh}{t}\right) * Energy\ efficiency$$

Equation 8: Energy output
of an incineration process for waste type i and fraction j

The energy output of a biogas plant is calculated by multiplying the incoming waste (after sorting) with a methane yield factor and the calorific value of methane (Equation 9).

$$Biogass\ out_i \left(\frac{kwh}{yr}\right) = Waste\ inflow_i \left(\frac{t}{yr}\right) * Methane\ yield \left(\frac{Nm^3}{t}\right) * LHV \left(\frac{kwh}{Nm^3}\right)$$

Equation 9: The biogas output of waste type i

To evaluate the performance of a scenario with respect to its recovered and required energy level, the energy efficiency is chosen as an indicator (Equation 10). This can be defined as "the amount of energy recovered over the amount of energy inputs in the system".

$$\eta_{energy} = \frac{Biogas\ out + energy\ out}{Transport\ energy + Process\ energy + Calorific\ value\ waste\ input}$$

Equation 10: Energy efficiency

4.2.3 Emissions

To quantify the environmental impact of the waste management system, the generated emissions are calculated. Four emission sources are included in this study; transport, sorting processes, recycling processes and incineration emissions. Landfill emissions are not included.

Transport and sorting emissions are calculated based on their energy requirement in the energy layer. The total energy consumption for each energy carrier is multiplied with its emission factor (Table 4). This means that no comprehensive LCA study is carried out to calculate these emissions. Emissions from the construction and materials of these processes are thus not included. However, as the transport emissions are expected to present only a small share of the total emissions (section 2.2.1), the total emissions will only be slightly underestimated.

Energy carrier	Kg CO2e./kwh	Source
Heavy fuel oil	0.3413	Ecoinvent 2.2
Diesel	0.2732	(Schmied, Knörr, Friedl, & Hepburn, 2012)
Natural gas	0.2577	Ecoinvent 2.2
Heat	0.1390	Appendix A.4
Electricity (NO)	0.0441	Ecoinvent 2.2
Biogas	0.0000	Biogenic emissions

Table 4: Emissions factors

The recycling and incineration emissions are based on the material layer. The material layer provides us with a detailed overview of each waste type and fraction that has been incinerated or recycled. These flows are then multiplied with the global warming potential (GWP) to calculate the environmental impact (Table 5). As hazardous waste and textiles follow the residual waste stream to incineration, no recycling emissions are given for these fractions.

Waste Fraction	Incineration (Kg CO2e. /kg)	Recycling (Kg CO2e. /kg)
Glass	0.0244	0.857
Metal	0.0190	0.051
Plastic	2.3478	0.666
Organic	0.0310	0.006
P&C	0.0245	0.672
Residual waste	0.5046	-
Hazardous	1.4279	-
Textiles	0.1454	-

Table 5: GWP for the incineration of different waste fractions
Incineration data (Ecoinvent 2.2), Recycling processes (Raadal et al., 2009).

Besides the generated emissions from the energy layer, the avoided emissions from recycling are also included in the analysis. The avoided emissions are calculated by multiplying the amount of a specific fraction that has been recycled with its avoided emission factor. Due to the time constraints of this study, avoided emission factors were not calculated for this specific case study. Instead, the average avoided emissions per waste fraction for Norway will be used (Table 6).

Fraction	Emissions	Unit
Glass	-0.895	Kg CO2e./kg
Metal	-2.589	Kg CO2e./kg
Plastic	-1.783	Kg CO2e./kg
P&C	-0.976	Kg CO2e./kg
Organic	-0.273	Kg CO2e./kwh
Residual waste	-0.160	Kg CO2e./kwh

Table 6: Avoided emission factors (Raadal et al., 2009)
Data for organic and residual waste are case specific.

The avoided emissions from organic and residual waste are calculated based on the energy output from the energy layer. Biogas generated from organic waste is replacing the consumption of diesel, therefore the emission factor from diesel (Table 4) is used to quantify the avoided emissions. Incineration of waste generates both heat and power. The generated heat is mostly used in a district heating system; hence it replaces other power sources used in district heating. It was assumed that the generated heat from waste will replace the use of oil and gas in a district heating system. The generated power is assumed to replace the Norwegian electricity mix (appendix A.4).

The total environmental impact will be calculated by summing both the generated and avoided emissions. A negative environmental impact means that the waste management system leads to a reduction in global emissions. A positive climate impact increases the global GHG emissions.

4.3 Sensitivity analysis

A sensitivity analysis is used to analyse the impact of certain parameters on the result. By deliberately changing the input value of a parameter, one can study the change in result to evaluate its robustness (Equation 11). Parameters that are sensitive should have a low degree of uncertainty to strengthen the results.

$$SR_p = \frac{\Delta R/R}{\Delta P/P}$$

Equation 11: Sensitivity ratio for parameter P on result R

Transfer coefficients for sorting and recycling processes are obtained from conversations with each different actor in the value chain. In most cases, data was not available to verify the transfer coefficients, hence they are classified as rather uncertain. The transfer coefficients from the sorting and recycling processes are therefore tested in the sensitivity analysis. Such an analysis can also be used to provide information on which parameter should be targeted for improvement. The transfer coefficients will therefore be evaluated on their impact on the material recycling rate, energy efficiency and environmental benefit.

5 Scenarios

To develop effective strategies towards circularity, multiple scenarios are developed. These scenarios are used to test different strategies and to analyse how they will perform on the indicators presented above. To compare the strategies with the European target by 2030, they will be implemented in the year 2022 and 2030. The year 2022 will hereby serve as a checkpoint towards 2030. The only parameter that is changing over the years is the population, the amount of waste generated per capita is assumed to be equal (Table 7). This means that the impact of waste reduction is not included in this study. The reference scenarios for 2022 and 2030 present the case where no measures are taken to improve the waste management system. The number of inhabitants and amount of waste are thus the only factors that change.

Year	Inhabitants	Waste (tonnes)
2016	194769	49340
2022	212769	53902
2030	236769	59989

Table 7: Number of inhabitants and waste

Data given by (ROAF, 2016) *and the assumption for equal generation of waste per capita*

Collection efficiency will be the main factor that changes over the different scenarios. The model allows us to change the collection technology mix to improve the collection efficiencies. However, these measures require specific waste compositions for each waste type and technology. Data that is currently not available (section 4.2.1). Therefore, a behavioural change by the households is assumed to generate purer waste streams. The waste composition of the small bins is adjusted to generate the targeted collection efficiency in each (appendix A.5).

5.1 Scenarios for 2022

As RoAF is planning to implement a three-bin system soon (section 3.2), the implementation of a G&M collection system is tested in the first scenario. Based on the experiences from other waste companies, the amount of G&M collected was assumed to increase from 11 kg/cap to 17 kg/cap (Bjørndal, 2016). The collection efficiency for glass and metal was increased to 90% and 75% respectively, leading to a collection efficiency for G&M of 87% (Table 8). The collection technology mix was assumed to be the same as the one used for P&C, mobile vacuum systems are not used (appendix A.5a). Small bins and containers are collected every 10 weeks, whereas underground containers are collected once every two weeks. Each bin is assumed to be collected with a biodiesel car, except for the underground containers that are emptied with one of RoAF's own car which are diesel fuelled (appendix A.5a).

To test the effect of a separate collection system for organic waste, the "organic bin" scenario was developed. As organic waste is believed to be one of the main factors influencing the central sorting facility (section 4.2.1), this scenario proposes to collect organic waste in a separate bin and send it directly to the biogas plant. Organic waste is thus not going through the sorting facility anymore. The collection efficiency of organic waste was assumed to be 80% (Miljødirektoratet, 2017b). The same collection technology mix, routes and vehicles are used as with RW. Organic waste is assumed to be collected once every two weeks (appendix A.5b).

The "more GB" scenario studies the effect of a higher collection efficiency of organic waste while maintaining the current system of green bags. The total amount of organic waste collected in green bags is thus increasing (appendix A.5e). In contrast to the other scenarios, this scenario includes the effect of cleaner materials in the sorting facility. More green bags mean a lower amount of organic waste in the RW bin, which delivers cleaner plastics. This is assumed to enhance the sorting of plastics. To quantify this relation, a linear regression is carried out on only two points (Figure 6). The first point representing the collection efficiency of organic waste in the reference scenario (44%) and todays transfer coefficient for plastic (36%). The other point assumes that no plastic would be sorted with an organic collection efficiency of 15%.

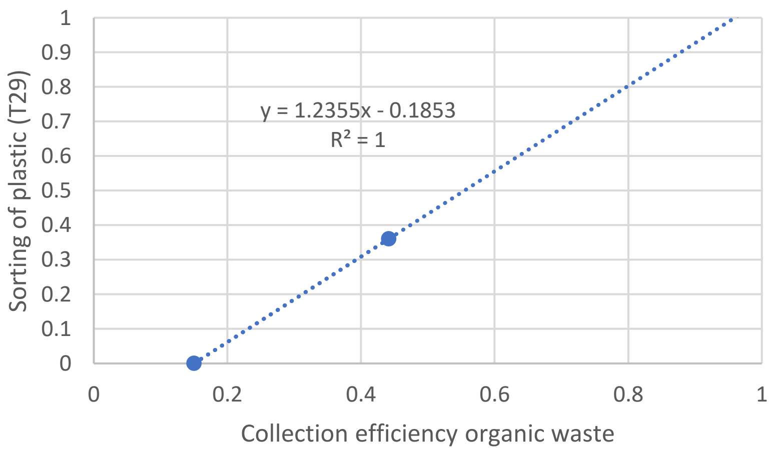


Figure 6: Performance of the central sorting facility dependent on the collection efficiency of organic waste

Even though this function is highly uncertain, it is likely to give us a more realistic result compared with neglecting this relation. The collection efficiency of organic waste in this scenario is assumed to be 60%, which results in a plastic sorting efficiency of 56%. The collection of G&M will also be implemented in this scenario. As RoAF has decided to implement the collection of G&M soon, this will increase the relevance of the scenario.

5.2 Scenarios for 2030

For the "perfect collection" scenario, both the G&M collection and organic bin scenario were implemented. Together with other measures, this is assumed to lead to a 100% collection efficiency for all fractions (appendix A.5c). Even though this outcome is considered very unlikely, it provides us with an upper bound for what is possible with improvements in collection only. Technologies (transfer coefficients) are not changed in this scenario.

In contrast to the previous scenario, the "perfect SAR" focuses purely on the improvement of technology in the waste management system. Because of its importance in Norway's waste management plans (section 2.3.2), the potential of the central sorting facility is tested in this scenario. The transfer coefficients for metal and P&C are increased to 100%. The transfer coefficient for plastic is assumed to increase to 80%. Syversen (2016) point out that currently only 69% of all plastic sent to the sorting facility can be sorted or recycled. This is mainly due to the colour or composition of some plastics. As RoAF is already influencing the composition of some plastic products (section 3.1), we assumed that the potential will increase to 80% by 2030 (appendix A.5d).

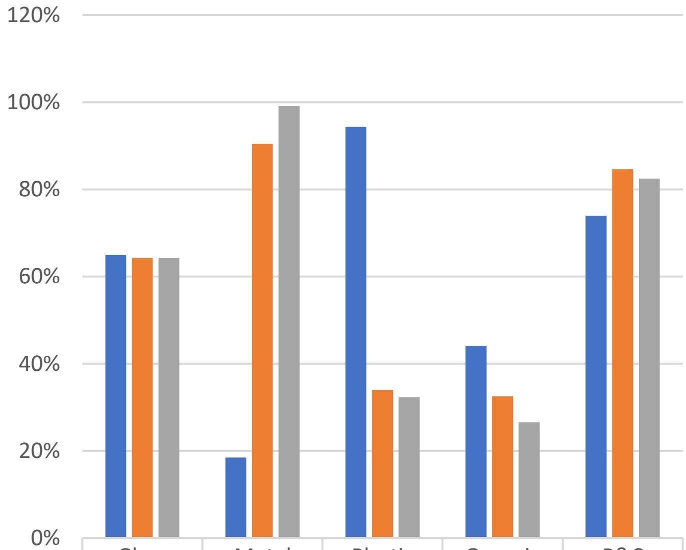
The final scenario builds upon the "more GB" scenario in 2020 and assumes a further increase in organic collection efficiency by 2030 (appendix A.5e). Organic collection is now assumed to be 75% which results in a plastic sorting efficiency of 74% (Table 8).

Parameter	2016 Reference	2022 GM collection	Organic bin	More GB	2030 Perfect collection	Perfect SAR	More GB
Collection Organic	44%	-	80%	60%	100%	-	75%
Collection Glass	65%	90%	-	90%	100%	-	90%
Collection Metal	18%	75%	-	75%	100%	-	75%
T29 plastic	36%	-	-	56%	-	80%	74%

Table 8: Overview of the scenarios and their change in parameter

6 Results

The reference scenario for 2016 has an overall recycling rate of 38% and the operations of RoAF delivers a 42% recycling rate (Figure 10). This is similar to the recycling rate RoAF calculated (section 3.2). The overall collection and sorting efficiency is 59% and 41% (appendix A.6a). When the collection, sorting and recycling efficiency are broken down for each waste fraction, the weak and strong points of the value chain become visible (Figure 7).



	Glass	Metal	Plastic	Organic	P&C
Collection efficiency	65%	18%	94%	44%	74%
Sorting efficiency	64%	90%	34%	33%	85%
Material Recycling	64%	99%	32%	27%	83%

Figure 7: Collection, sorting and recycling efficiency

One can observe two different trends for the waste fractions; a decreasing and an increasing efficiency over the value chain. The former presents the normal trend where the recycled amount decreases as it moves downstream. This trend can be observed for all waste fractions except for metal and P&C. For those fractions, the central sorting facility reverses the trend. Only 18% of all metal is collected at the G&M collection points, resulting in a high amount of metal in the RW bin. However, this is effectively separated from RW which results in a metal sorting efficiency of 90%. As all losses over the value chain are being incinerated and thus going to the bottom ash treatment facility, the recycling rate increases to almost 99%.

The performance of the sorting facility for plastic and organic waste shows the weak point. Almost all plastic is thrown in the correct RW bin but as discussed in section 4.2.1, the sorting machine only separates 36%. Downstream plastic losses however, are limited; only 5% of the plastic sent to recycling is not recycled (appendix A.2b). A low collection rate for organic waste and constant losses over the value chain, results in an organic material recycling rate of only 27%.

The results from the energy layer give an energy efficiency of 15%. 90% of the generated energy comes from incineration while only 10% is biogas (Figure 13). The calorific value of the waste being incinerated is observed to be 6.29 MJ/kg. This is significantly lower than the desired value of 11 MJ/kg specified for the Klemetsrud incineration plant (Norling, 2017). Lower amounts of plastic and P&C due to the sorting facility explain the difference. In addition, wood (waste) often represents a significant share of the MSW mix which increases the calorific value. However, the amount of wood is our MSW mix only represents 0.7% of the total waste (Syversen & Bjørnerud, 2016). The energy inputs are for 92% represented by feedstock energy. When this share is left out, transport energy accounts for 18% and process energy for 82% of the total inputs. Collection transport energy covers 40% of the total transport energy. The other share represents downstream transport.

The emissions generated by the system are bigger than the avoided emissions (Table 9). This means that the system is contributing to the global emissions. It can be observed that transport and sorting processes only represent 5% of the total emissions. The central sorting machine is responsible for 92% of the sorting emissions. However, as more data was available for the central sorting facility than for the other sorting processes, this share is most likely too high.

Emissions	Kg CO2 e./Inhabitant
Avoided	122.82
Generated	-120.79
Transport	4%
Sorting	1%
Recycling	39%
Incineration	56%

Table 9: Generated and avoided emissions under the reference scenario

Collection transport emissions represent 17% of the total transport emissions. The collection of residual waste in area four (Aurskog-Høland and Rømskog) shows to have the biggest impact on the total collection emissions (Figure 8). This can be explained by the lack of biofuel cars from the contractor in that area. One can observe that the collection of P&C at households generates less emissions than the collection of G&M at collection points. The high share of bio fuelled cars in area 1,2 and 3 compared to a total lack of bio fuelled cars for G&M explains the difference.

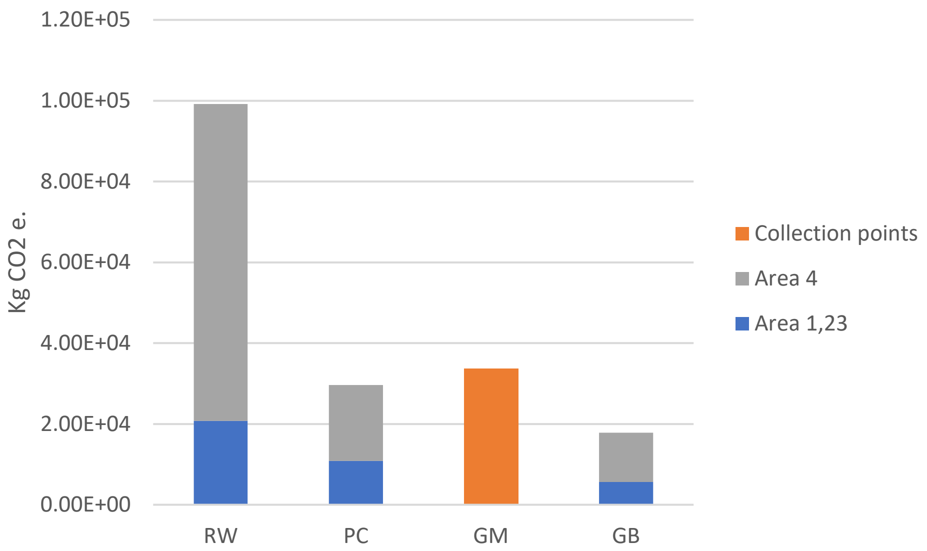


Figure 8: Transport emissions over different areas and waste types

Based on the current waste management system organized by RoAF, plastic is the main source of the emissions (Figure 9). Still 68% of all plastic is incinerated, generating a high amount of emissions. One can observe that the avoided emissions from incinerating plastic are remarkably lower than the generated emissions. For the recycling of plastic however, this is the opposite. Together with residual waste, these are the waste fractions that currently generate more emissions than they avoid. The other fractions generate a climate benefit to various degrees. P&C generates the biggest climate benefit mainly due to its quantity (appendix A.6a). The recycling of P&C shows also to be the major source for both the avoided emissions and the recycling emissions. Despite small quantities, metal recycling gives a climate benefit mainly due to its low recycling emissions and high avoided emissions per kg metal. Glass recycling on the other hand has a lower climate benefit. The high recycling emissions almost compensate for the avoided emissions.

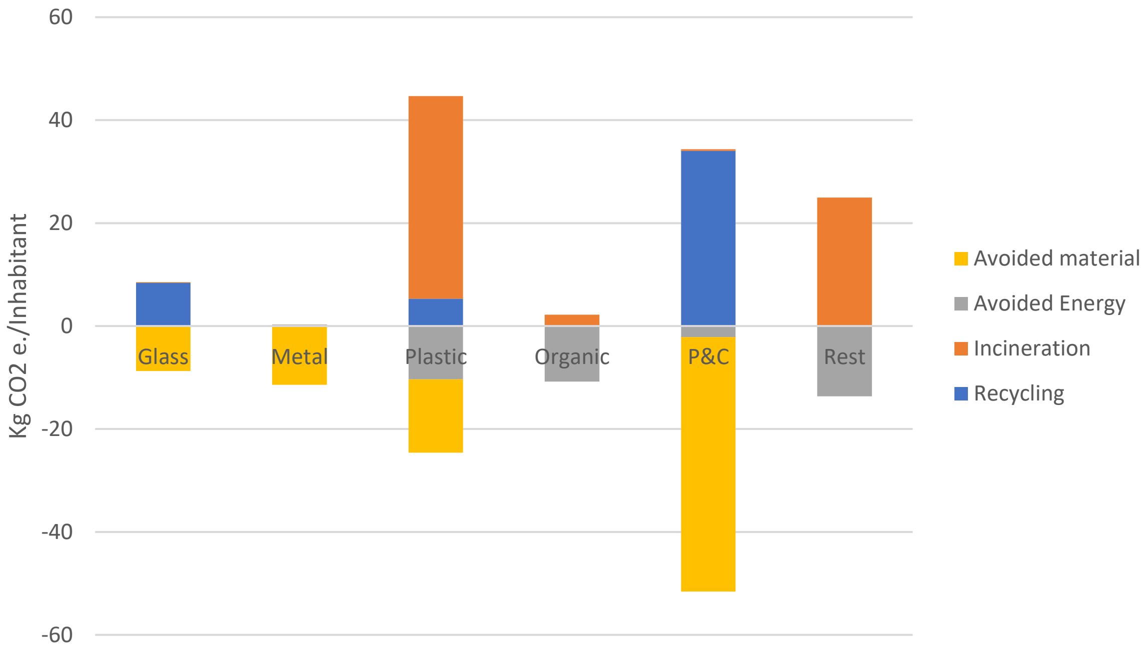


Figure 9: Generated and avoided emissions due to the paths and destinations of each waste fraction caused by the current waste management system (excl. emissions from transport and sorting)

The impact of the central sorting facility on the results presented above were tested in a sensitivity analysis (Table 10). Focussing on the recycling rate, one can observe a significant impact from the sorting of GB. A 1% increase in the GB sorting will lead to an increase of 0.25% for the overall recycling rate. Organic waste presents the largest share of the waste entering the facility, hence it will have a bigger influence on the overall recycling rate than the other fractions. The energy efficiency is mainly influenced by the sorting of plastics. Increased plastic recycling will generate lower energy from incineration and higher energy needs due to transport and recycling processes. In contrast, organic waste has a positive influence on the energy efficiency. Recycling organic waste requires less energy inputs and generates more energy compared with incineration. Improved plastic sorting is shown to be highly beneficial for the environment. A 1% increase of sorting, leads to a decrease in net emissions with 11.03%. As the avoided emissions slightly increase due to a shift from energy to material recycling, the climate benefits will mainly come from lower incineration emissions. High recycling emissions for P&C result in a low climate benefit for improved P&C sorting.

TC	Fraction	Recycling rate	Energy efficiency	Climate impact
T29	Plastic	0.082%	-0.152%	-11.03%
T29	Metal	0.002%	-0.001%	-0.28%
T29	P&C	0.066%	-0.041%	-0.30%
T27	Organic	0.250%	0.060%	-2.97%

Table 10: Sensitivity analysis for the performance of the central sorting facility based on a 1% increase in transfer coefficients

6.1 Scenarios for 2022

The reference scenario for 2022 has the same collection, sorting, recycling and energy efficiency as in 2016. As the number of inhabitants increases. and thereby also the amount of waste, the process and transport energy requirement will increase with 2060 Mwh and 463 Mwh respectively. In addition, the total emissions increase with 2200t CO2e. This scenario entails no changes in the waste management system and will therefore be used as a reference scenario for the other scenarios in 2022.

The "**GM collection**" scenario results in a recycling rate of 40% (Figure 10). The minor increase in recycling rate is due to the small amount of G&M compared with the total waste generated (appendix A.5a).

Collecting G&M at households is more energy intensive than the current system of collection points. Together with the increased amount of G&M collected, this will result in a 63% increase of transport energy for the collection of G&M. However, increasing the collection efficiency of G&M results also in a lower weight for the RW bin. Thereby limiting the total increase of collection energy to 2% (appendix A.6d). The decrease in process energy required by the system compensates the increase in transport energy. Diverting 878t G&M from incineration to recycling generates a higher energy requirement for G&M sorting and recycling processes. However, a significant decrease in the use of auxiliary fuels at the incineration plant combined with less energy consumption at the central sorting and bottom ash treatment plant, results in an overall decrease in energy demand. As G&M generates no heat in an incineration plant, the generated amount of energy will almost remain unchanged. The energy efficiency will therefore also be unchanged (Figure 10).

Despite the lower energy requirements of the system, the generated emissions increase with 2.5% or 665t CO2e (appendix A.6d). The main source is the increase in recycling emissions, mostly related to glass recycling. Transport emissions are observed to increase slightly due to increased downstream transport. Collection emissions on the other hand decrease with 21t CO2e due to the use of biogas vehicles instead of diesel vehicles. As G&M generated a high amount of avoided emissions, the total environmental impact is observed to decrease with 70t CO2e.

The "**organic bin**" scenario results in a recycling rate of 53% for the total waste management system and 59% for RoAF (Figure 10). This increase of 15 pp is due to the doubling of organic waste being recycled (appendix A.6b).

Energy efficiency is observed to increase 1.5 pp to 16%. Effective handling of organic waste results in an increase of biogas production with 153% or 8246 Mwh. This compensates the decrease in energy production from the incineration plant resulting in a higher energy output. Using a separate collection vehicle for organic waste, increases the collection energy requirement with 5%. One should note that the decrease in residual waste and the shift from a weekly to a two-weekly organic collection system are the main factors limiting the increase in collection energy. Transporting the organic waste directly to the biogas plant results in a lower amount of organic waste being incinerated, hence downstream transport energy decreases with 8%. The decrease in waste being sorted and incinerated, results in a lower process energy demand. As the external energy requirement from the biogas plant is rather low, the total process energy demand decreases with 5%. Furthermore, increased organic recycling results in a higher burning value for the waste at the incineration plant. The LHV of the MSW mix increases to 7.65 MJ/kg.

Total generated emissions decrease with 1.2% or 311t CO2e. Increased emissions from recycling are compensated by the lower emissions from incineration. Furthermore, less organic waste going through the sorting facility decreases the sorting emissions with 35%. The collection of organic waste includes a higher energy requirement and thus higher emissions. The increase in emissions is however limited to only 4% using biogas vehicles. As the production of biogas is more than doubled and it is assumed to replace diesel, the avoided emissions increase with 7%. This results in the avoided emissions being higher than the generated emissions. The entire waste management system creates a climate benefit of 8 kg CO2e./inhabitant (Table 11)

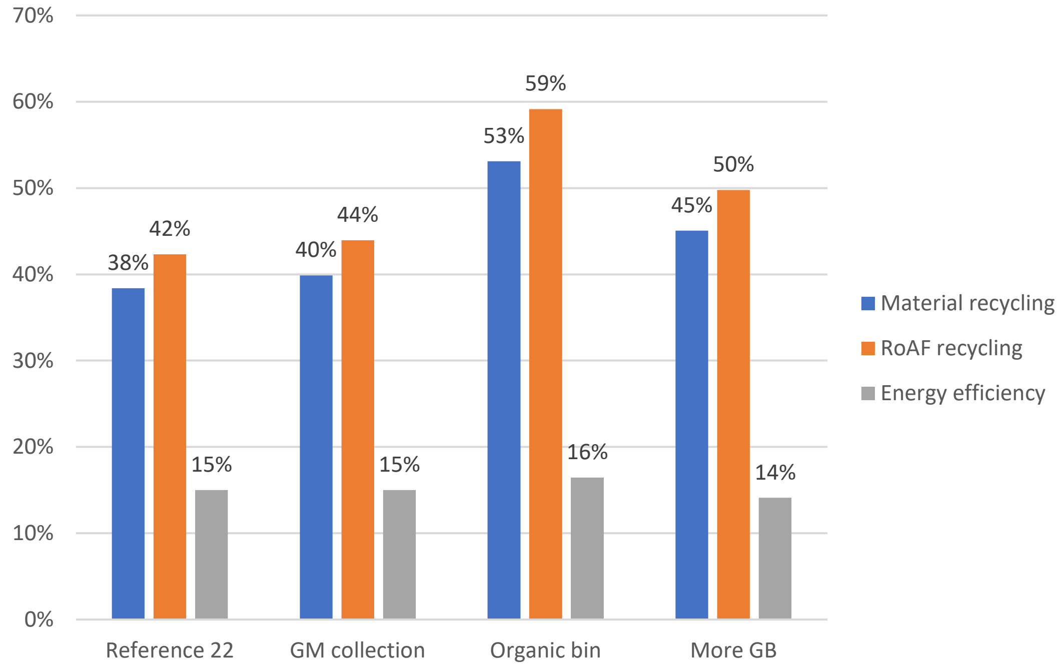


Figure 10: Collection, sorting and recycling efficiency for the different scenarios in 2022

The "**more GB**" scenario results in a 5 pp increase of recycling rate compared with the GM collection scenario. For RoAF, a recycling rate of 50% can be achieved (Figure 10). When analysing the individual recycling rates, one can see a plastic recycling rate of 50% and an organic recycling rate of 36%.

Diverting 925t plastic and 1807t organic waste from incineration to recycling decreases the total energy generation with 6%. In contrast to the previous scenario, increased biogas production does not compensate the lower amount of energy generated from incineration. One can also notice that the lower amount of plastic and organic waste sent to the incineration, has only a small impact on the LHV of the MSW mix. The LHV increases from 6.29 MJ/kg to 6.32 MJ/kg. Increased plastic recycling results in a 2% increase in energy consumption. In addition to that, also downstream transport increases. Incineration plants are generally located closer to the waste collection system than plastic recycling plants. The decrease in energy generation and increase in energy requirement results in an energy efficiency of 14%.

The emissions generated by the recycling process of plastic and G&M increase with 13%. However, the incineration emissions are reduced with 15% and due to the implementation of G&M collection, less energy and emissions are used in the sorting and bottom ash treatment facility. Transport emissions on the other hand increase by 4% because of more downstream transport. As this only has a small impact on the total emissions, the measures taken in this scenario result in an overall reduction in emissions of 892t CO2e. The decrease in energy generation results in a 2% reduction in avoided emissions related to energy recovery. But because virgin plastic requires a high amount of fossil fuels, increased material recycling lowers the climate impact to -13 kg CO2e./inhabitant (Table 11). The waste management system generates thus a climate benefit.

Emissions	Reference 22	GM collection	Organic bin	More GB
Generated	123	126	121	119
Avoided	-121	-124	-129	-131
Netto	2	2	-8	-13

Table 11: Generated and avoided emissions for each scenario in 2020 (Kg CO2e./Inhabitant)

6.2 Scenarios for 2030

Like the reference scenarios from 2016 and 2020, the material recycling rate will be 38% for the total MSW system and 42% for RoAF. Due to the increased number of inhabitants, the process energy requirement will increase with 8246 Mwh compared to 2016. Transport energy will increase with 1091 Mwh. The total emissions generated by handling waste as it is done today, will increase with 5195t CO2e.

The "**perfect collection**" scenario has the highest recycling rate of all the scenarios (Figure 11). RoAF reports a recycling rate of 72% whereas the total system just reaches the circular economy targets of 65% recycling. Again, organic waste is the main contributor leading to more recycling. In addition, also 2182t P&C and 1252t G&M extra are recycled (appendix A.6c).

Alike the organic bin scenario, the energy efficiency increases to 16%. The high amount of organic waste being recycled results in tripling the production of biogas (appendix A.6c). This compensates the lower energy generation at the incineration plant resulting in an increase of generated energy with 7%. The increased recycling of organic waste also involves an increase in LHV for the MSW mix to 9.19 MJ/kg. The process energy requirement increases with 4.5% due to more glass and P&C recycling. Because the central sorting facility has not improved in this scenario, plastic recycling remains almost equal compared with the reference scenario (Figure 12). Therefore, no increase in energy demand for plastic recycling is observed. Collection energy increases with 13%. While more energy is required to collect G&M, P&C and GB, the energy requirement of collection RW decreases with 40%. Despite longer transport distances for recycling, downstream transport experiences no significant changes. Short but multiple trips to the incineration plant are replaced by longer but fewer trips to recycling plants.

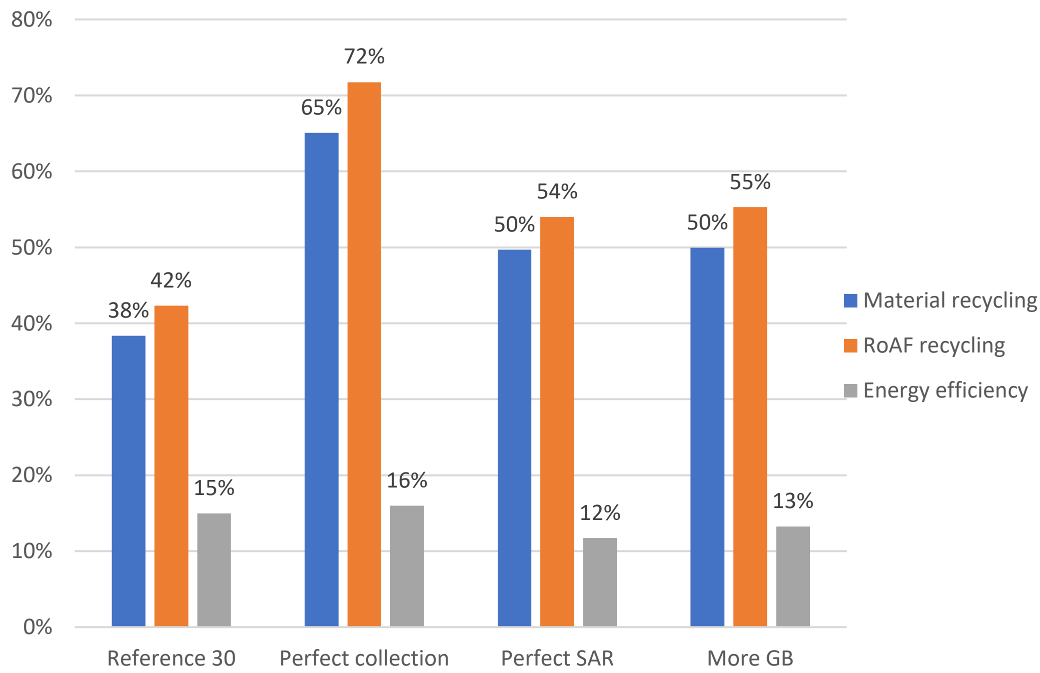


Figure 11: Collection, sorting and recycling efficiency for the different scenarios in 2030

The higher process energy requirements result in an increase of emissions with 1865t CO2e. Incineration emissions only decrease slightly as the amount of plastic being incinerated remains almost unchanged. Perfect collection entails less waste going through the central sorting facility, hence sorting emissions decreased with 50%. In addition, also the transport emissions are observed to decrease. As this scenario implements both the G&M collection and organic bin scenario, an increasing amount of biogas vehicles are used to collected the waste at households This decrease in emissions is not sufficient to compensate the higher emissions caused by increased recycling. Nevertheless, the avoided emissions increase with 20% resulting in a net climate benefit of 15 kgCO2e./inhabitants (Table 12). Tripling the biogas production leads to an increase in avoided emissions related to energy generation of 27%. Avoided emissions due to material recycling increase with 17%.

The "**perfect SAR**" scenario results in a recycling rate of 50% (Figure 11). In contrast to the previous scenario, more plastic recycling is the biggest contributor to the increase in recycling rate (Figure 12). One could conclude that a 50% recycling rate is rather low for a perfect central sorting facility. As the collection efficiency is not improved in this scenario, still 55% of the organic waste is not collected in the green bags and thus incinerated. This narrows the increase in total recycling rate.

The energy efficiency decreases with 22%, from 15% to 12%. Due to increased plastic recycling, the energy produced from incineration decreases with 22%. Better sorting from the sorting facility results in a minor increase of biogas production. This is not enough to compensate the decrease in incineration, hence energy production decreases with 28%. Diverting plastic from incineration but maintaining the supply of organic waste results in a LHV of the MSW mix of 5.57 MJ/kg. Recycling plastic and P&C requires a significant amount of energy. Therefore, the increase in energy requirement is mainly due to increased process

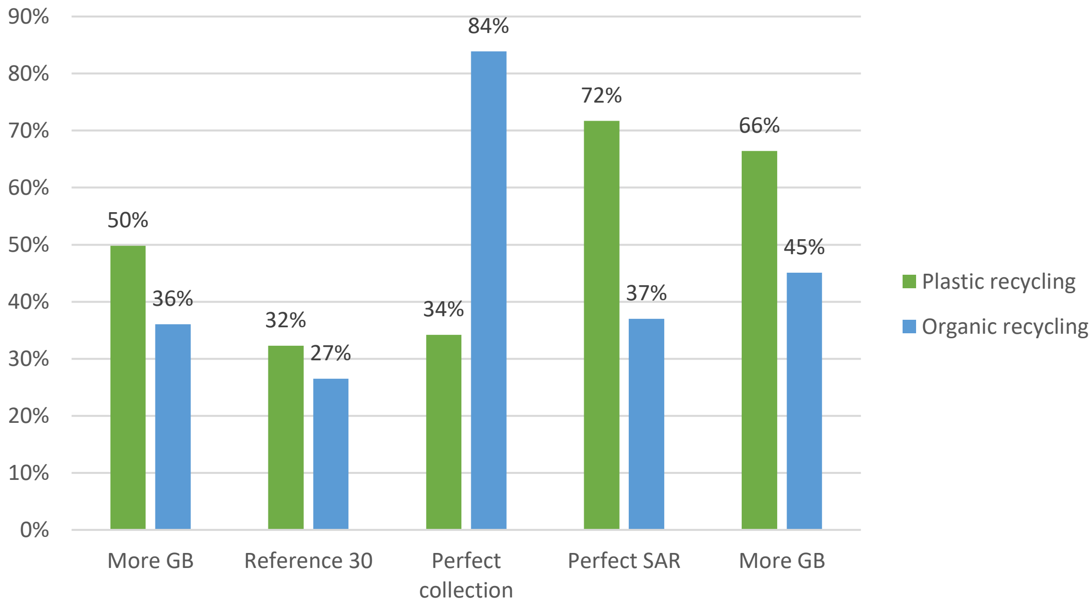


Figure 12: Plastic and organic recycling rate over the different scenarios in 2030

energy. But also transport energy consumption increases. In contrast to the previous scenario, increased transport to recycling facilities is not compensated by less transport from the sorting facility. A substantial amount of organic waste is still transported to the incineration plant, hence the total transport energy requirement will increase with 11% (appendix A.6d).

More plastic recycling results in an increase in recycling emissions with 26%. As mentioned before, this leads to more downstream transport and therefore transport emissions increase with 15%. However, the total emissions decrease with 2352t CO2e. A significant decrease in incineration emissions compensates the increase in process and transport emissions. As energy production decreases significantly in this scenario, the related avoided emissions decrease with 15%. This is compensated by the increase in avoided emissions due to increased (plastic) recycling. The MSW management system generates a high climate benefit of 29 kgCO2e./inhabitant.

The “**more GB**” scenario has a slightly higher recycling rate compared with the previous scenario (Figure 11). The organic recycling rate increases to 45% (Figure 12), thereby contributing to an increase in recycling rate compared with the reference scenario. Better functioning of the central sorting machine results in a plastic recycling rate of 66%.

As more plastic has been recycled, energy production from incineration decreases with 20%. Better organic collection results in a 70% increase in biogas production. Thereby limiting the decrease in energy production to 10% (Figure 13). Recycling more plastic and organic waste

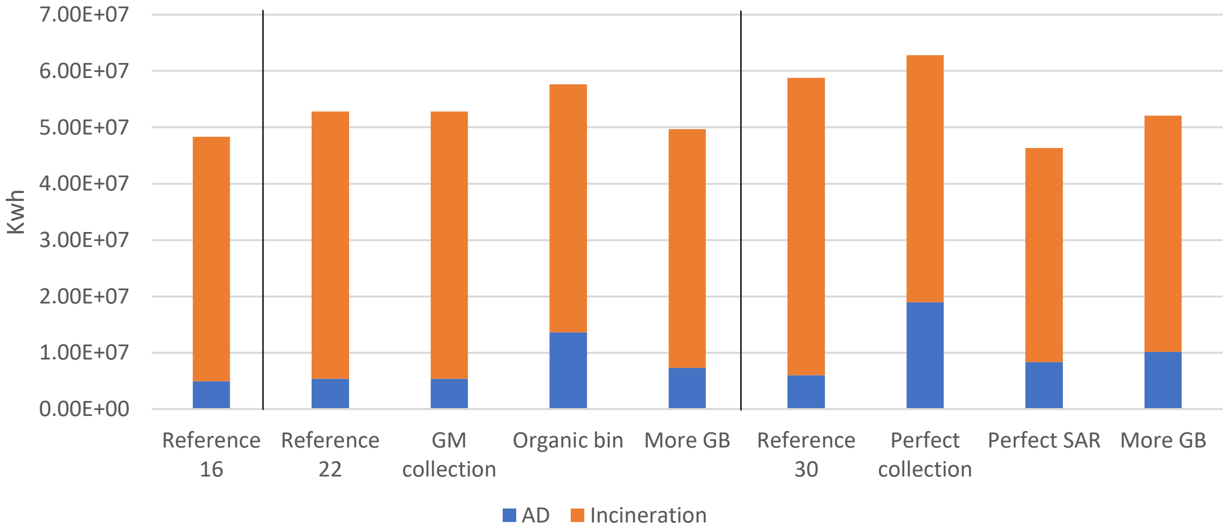


Figure 13: Generated energy from anaerobic digestion and incineration of waste for each scenario

compared with the "more GB" scenario in 2022 results in a lower LHV of 6.15 MJ/kg. In addition, both the process and transport energy requirement increase. Process energy demand increases with almost 4%, which is lower than the 11% increase in the perfect SAR scenario. This is mainly due to less P&C being recycled in this scenario compared with the previous scenario. More plastic recycling however results in an increase in downstream transport of 8%. A higher energy demand by the system combined with a decrease in energy production results in an energy efficiency of 13%.

The total amount of emissions decreases with 2631t CO2e. Increased plastic recycling results in an increase of recycling emissions with 18%. Also transport emissions increase due to more downstream transport. Nevertheless, these emissions are compensated by the decrease in incineration. More biogas production almost compensates the lower energy production of waste and thus a dirtier district heating system. The avoided emissions from energy recovery decrease with 4%. However, increased plastic recycling results in an overall increase of avoided emissions of 14%. Together with a decrease in generated emissions, this results in a climate benefit of 26 kg CO2e./inhabitant.

Emissions	Reference 30	Perfect Collection	Perfect SAR	More GB
Generated	123	131	113	112
Avoided	-121	-145	-142	-138
Netto	2	-15	-29	-26

Table 12: Generated and avoided emissions for each scenario in 2030 (Kg CO2e./Inhabitant)

7 Discussion

7.1 Findings

Despite having a central sorting facility, a high collection efficiency remains crucial for the waste management system. Besides sorting plastics and green bags, the facility also separates paper and metal. As seen in Figure 7, this reduces the consequences of lower collection efficiencies for paper and metal. When discarded incorrectly, these fractions have a second change on recycling. Especially for metal, the sorting has proved to be very useful. However, some consequences from having lower collection efficiencies for these fractions should be discussed. First, it leads to higher energy requirements. The sorting facility has a higher energy requirement compared with the other downstream sorting process it replaces. This was observed in the GM collection scenario where the decrease in process energy from the central sorting facility was bigger than the increase from the GM sorting facility. Secondly, lower collection efficiencies for glass and metal are likely to result in more damage for the green bags. The sharp edges from metal and glass waste surrounding the green bags in the collection vehicle increase the chance of damage to the bags. Thirdly, lower collection efficiencies lead to a bigger role for technology in the recycling process. When discarded correctly, metal and paper follow a flow towards recycling. Sorting errors lead to impurities in the recycled material and therefore a lower quality of the secondary material. In contrast, when discarded incorrectly, these fractions follow a flow towards the incineration plant. Technology defects result in incineration and not in a lower quality of secondary material. Lower collection efficiencies are therefore more likely to result in lower recycling rates.

The importance from higher collection efficiencies is highlighted by the results of all the scenarios. All the scenarios except the “more GB” and “perfect SAR” scenario focus on better collection efficiencies to increase recycling and climate benefits. As all the scenarios result in lower netto emissions, better collection proves to be beneficial even with a central sorting facility providing a second change for some fractions. A collection decision should therefore be analysed, based on the entire performance of the system. In the “organic bin” scenario, collection energy and emissions increase because of increased household collection. Implementing this scenario could thus be considered harming the environment at first sight. However, the results show the opposite, the overall climate impact is reduced with 10 kg CO2e./inhabitant (Table 12).

The sorting of plastic and collection of organic waste has shown to be crucial for the improvement of the value chain. As observed in Figure 7, plastic and organic waste have currently the lowest material recycling rate. Not surprisingly, both fractions rely mostly on the performance of the sorting facility to be recycled. The sensitivity analysis showed therefore a significant impact for both plastic and organic waste (Table 10). Focusing on the improvement of the central sorting machine result in clear environmental benefits but cannot be considered as the solution to solve all waste collection problems. As observed in the “perfect SAR” scenario, substantial amounts of organic waste were incinerated, leading to a relatively low overall recycling rate. This because organic waste also relies on appropriate collection to be recycled. Without improved collection, perfect sorting will only result in using a small share of the potential organic waste has for recycling. Furthermore, improved organic collection is also expected to influence plastic sorting. As observed in the “more GB” scenarios, this relationship has a high impact on the performance of the waste management system. Both the material recycling rate and climate benefit increase significantly, stressing the importance of organic collection once more.

Multiple methods can be used to increase organic collection. Collecting organic waste in a separate bin showed to have a significant impact on the indicators. However, this is entirely dependent on the collection efficiency the separate bin was assumed to generate. The outcome of this scenario illustrates therefore more the potential of a higher organic collection than the results from implementing a separate organic bin. Higher collection efficiencies could for example also be achieved by using the green bags. In this, better communication and collection technologies are likely to play a significant role. Organic bins and green bags could also be implemented together. Urban areas with less space for separate bins could continue to use the green bags whereas other, more specious areas could implement a separate bin. This decreases the number of green bags going through the sorting facility, and thereby also the chance of polluting other fractions throughout the value chain. Communicating this differentiated system to the households could however be challenging.

Increased organic recycling limits but does not compensate the energy efficiency losses generated by increased plastic recycling. Recycling plastic has a negative impact on energy efficiency but generates an overall climate benefit. This trade-off, identified by the sensitivity analysis, was observed in detail in the “perfect SAR” scenario. This scenario has the highest plastic recycling rate and climate benefit, but the lowest amount of energy generated and therefore also the lowest energy efficiency. Other scenarios however, show that the losses in energy generation could be compensated by improved organic recycling. As the sensitivity analysis showed, improving organic sorting is the only measure that has a positive effect on material recycling, energy efficiency and climate benefit. The “organic bin” and “perfect collection” scenario are therefore the only scenarios that report an increase in generated energy and energy efficiency. Increased biogas production compensates the losses in heat and power from the incineration plant (Figure 13). Nevertheless, when the relation between organic collection and plastic sorting is included, a decrease in energy efficiency will be inevitable. The “more GB” scenarios limit the losses by increased biogas production, but a decrease in energy efficiency and generation is still observed.

Despite a lower energy efficiency, increased recycling does generate overall climate benefits. Less waste going to the incineration plant results in a higher use of auxiliary fuels to meet the demand for district heating. This was included by increasing the share of oil and gas in the avoided district heating mix (appendix A.4). However, the higher emissions from dirtier energy generation do not compensate the benefits from recycling. Incinerating plastic generates, besides energy, also a substantial amount of emissions. If one focuses purely on the generated emissions, it can be observed that the “perfect collection” scenario is the only scenario in 2030 with an increase in generated emissions (Table 12). Plastic recycling is in this scenario only slightly improved, which results in a small decrease in incineration emissions. Not enough to compensate the increase in recycling emissions. The “perfect SAR” scenario on the other hand, shows that the reduction in incineration emissions from plastic can compensate the increased recycling emissions from all the other fractions. Furthermore, as the avoided emissions from recycling plastic are bigger than those from incineration, climate benefits are generated both by a reduction in generated emissions and an increase in avoided emissions.

A shift from energy generation to material recycling has can also influence the operation of the incineration plants. Incineration plants are built to handle a certain type of waste. A too high LHV of the MSW mix could therefore damage the installation. To prevent this from happening, organic waste is commonly used to achieve the desired LHV for the waste entering the incineration plant. Diverting organic waste from incineration to recycling increases the LHV and can possibly harm the operation of the plant. This was observed in the “organic bin” and “perfect collection” scenario where the LHV increased from 6.29 MJ/kg to 7.65 MJ/kg and 9.19 MJ/kg respectively. However, increased organic recycling does not necessarily lead to a higher LHV. The “more GB” scenarios report a minor increase and even a decrease in LHV in

2030. These scenarios are effective in recycling plastic, which lowers the LHV of the MSW mix and thereby reduces the need for organic waste in the incineration plant.

The circular economy targets have shown to be hard to reach. The “perfect collection” scenario is the only scenario that meets the 65% target whereas the other scenarios face difficulties reaching a recycling rate of 55%. The magnitude of the gap exemplifies the difficulty of the task and stresses the importance of improved collection once more. Focussing on the biggest fractions has shown to be the most effective strategy to improve the recycling rate. Big fractions such as organic waste and P&C, present almost half of the total amount of household waste included in this study. Optimizing the value chain for these fractions will lead to significant improvements in the recycling rate. Focussing on improved G&M collection is therefore not an effective strategy to reach the targets. However, as glass represents the fourth biggest fraction, improving the collection of glass will be necessary to reach the targets once the biggest fractions are optimized. Furthermore, as the central sorting facility illustrates, separating minor fractions from the residual waste stream can be difficult and expensive. Improved collection of all fractions can therefore be considered necessary to increase the recycling rate close to the 65% target.

The highest material recycling rate does not necessarily result in the highest climate benefit. The “organic bin” and “perfect collection” scenario result in the highest recycling rate for 2022 and 2030 respectively. The highest climate benefits however are observed in the “more GB” and “perfect SAR” scenario. While organic waste has a significant impact on the overall material rate, plastic has a considerable impact on the climate benefit (Figure 12). In this context, the 55% recycling target of plastic packaging waste can be considered as necessary to ensure high climate benefits in the circular economy package. Without this target, the focus could move towards the biggest fractions such as organic waste and thereby delaying the biggest climate benefits to the end. Furthermore, as increased plastic recycling has negative effects for the energy generation in the system, the target lowers the chances for maintaining low plastic recycling rates due to other interests. Based on the discussion presented above, one can conclude that RoAF has a unique position to increase both its recycling rate and climate benefit with one action. Improving organic collection leads to both a higher recycling rate and a higher climate benefit due to better plastic sorting. This explains the overall satisfactory performance of the “more GB” scenarios.

As a central sorting facility mainly focuses on improving the recycling rate of plastic, this will not be sufficient to reach the 65% target. Improvements in collection efficiencies of all fractions are necessary to close the current gap. One could therefore conclude that cities with high collection efficiencies should be encouraged to keep their system and to cooperate with downstream actors to reduce downstream losses. A central sorting facility on the other hand should be implemented in cities with a low plastic collection efficiency. Considering improvements in the current performance of the facility, this is an effective strategy to increase plastic recycling, climate benefits and to reach the 55% target for plastic packaging. Furthermore, a central sorting facility can provide useful back-up sorting processes and facilitates separate collection of organic waste in urban areas. Thereby possibly improving the recycling of organic waste. When collaboration with downstream actors is not an option, a sorting facility could enable cities to gain control over the downstream sorting process. Cities that observe high downstream losses could use a sorting facility to ensure alignment with national recycling strategies and to increase environmental benefits.

Focussing on waste minimization can decrease the share of residual waste and increases the chance to reach the 65% target. The residual waste fraction presents currently almost 20% of the total amount of waste used in this study. This fraction is not appropriate for recycling which results in a maximum recycling rate of 80%. Minimizing this fraction could thus be considered as an effective strategy to increase the recycling rate and climate benefit. Diapers, plant residues and dirty plastic represent almost half of the residual waste fraction. In this context, RoAF's support for cloth diapers is highly relevant and should maybe be increased. Besides the residual waste fraction, reducing other fractions will also help to reach the targets. Focus on organic waste reducing is likely to increase over the years due to economic and ethical factors. This could decrease the amount of dirty plastics. This increases the share of recyclable plastic waste and decrease the weight of the residual and organic fraction. Furthermore, collaborating with food concerns to influence the plastic packaging will increase weight of plastic recycling. Considering a better performance of the sorting facility, these actions will help RoAF to reach the targets and to improve the climate benefit of the waste management system.

7.2 Strengths and weaknesses

The model allows for a detailed analysis of a complex interconnected system. By breaking down each waste type, one can analyse the performance of the system for each fraction. Applying this across the different waste types gives the user a basis for calculating the collection efficiencies. This method identified a low collection efficiency for metal despite a high recycling rate. When moving downstream the value chain, this allows for tracking the origin of certain waste fractions. For the case of RoAF, most of the metal being recycled was discarded in the RW bin, stressing the importance of the central sorting facility for metal. However, a high amount of plastic and organic waste entering the incineration plant originates from the RW bin and GB. Indication severe sorting shortcomings. Furthermore, an analysis based on waste fractions facilitates the calculation of individual indicators (Figure 7). This was proven to be an effective method to for identifying the biggest losses over the value chain.

Maintaining this throughout the energy and emission layer increases the quality of the results. Emissions from incinerating MSW are commonly based on an average MSW mix. This delivers good aggregate result, but could significantly differ from local conditions. Based on the results from the material layer, it is possible to calculate the incineration emissions based on the local MWS mix. Similarly, energy generation from incineration is highly dependent on the waste mix. Using the material layer will therefore also reduce the uncertainty of the energy generation for different scenarios. Despite not being included in the study, the same can be done for a landfill. The MSW mix can be used to calculate the generation of landfill gas and emissions for the local waste management system. Finally, following the waste flows to the market for secondary materials can decrease the uncertainty in the avoided emissions. As sorting and recycling losses have a significant impact on the avoided emissions (Michaud et al., 2010), it is important to include these factors in the analysis. Sorting and recycling losses can be adjusted under each scenario or will decrease automatically due to an increased purity of the collected waste flows. This results in an accurate representation of the avoided emissions but requires the use of avoided emission factors that do not already include these factors.

The model includes the entire waste management system which makes it valuable for decision support. As discussed in section 2.4.2, most models lack a holistic perspective which makes it hard to estimate the total impact of a decision in a "system of systems". Using an MFA of the waste management system as the basis for the analysis, provides a possibility to overcome the complexity of the system. The interconnectivity of the different processes can easily be mapped by the quantification of some material flows. Furthermore, including both energy and emissions in the analysis enlarges the impact sphere. Coupling life cycle date with the MFA allows the decision maker to analyse the impact on various levels. This is likely to shift the impact from a local to a global optimum. In addition, the model can also be coupled to system engineering models such as optimization methods or a cost benefit analysis. Finally, it facilitates the testing of strategies and the development of pathways towards a circular economy. Waste management companies can adjust the model to their local value chain to test to impact of different strategies. Based on this, pathways focussing on improvements of the critical factors can be developed.

The flexibility of the model is obtained by a high data requirement. This provides the user the possibility to tailor the model to its needs, but makes it also more vulnerable for uncertain data sets. To analyse the quality of the results presented above, a sensitivity analysis was performed on the most important parameters. The sensitivity analysis studies the impact from a 1% increase of a parameter on a specific indicator. To compare these impacts, the normalized sensitivity ratio was introduced (Equation 12).

$$NSR_p = \frac{SR_p}{Max(|SR_p|)}$$

Equation 12: The Normalized sensitivity ratio for parameter p

This ratio normalizes the impact from each parameter over the highest impact. To classify the impact relative to the highest impact, various categories and colours are used (Table 13). A negative NSR identifies a negative relation between the parameter and the indicator; an increase of the parameter will result in a decrease of the indicator.

Category	Impact
0 < NSR < 0.1	Negligible
0.1 < NSR < 0.3	Low
0.3 < NSR < 0.6	Medium
0.6 < NSR < 0.8	High
0.8 < NSR < 1	Very high

Table 13: Categories used in the sensitivity analysis

As mentioned in section 4.3, the transfer coefficients were mainly obtained from communication with downstream actors. As no data was available to check the information, the impact from the transfer coefficients on each indicator was analysed. Because the individual recycling rates are an important indicator to analyse the performance of the value chain, this was included in the sensitivity analysis (Table 14).

Parameter	Fraction	Individual RR	Material recycling	Energy efficiency	Climate impact
T29	Plastic	1.00	0.33	-1.00	-1.00
T29	Metal	0.05	0.01	-0.01	-0.03
T29	P&C	0.13	0.26	-0.27	-0.03
T27	Organic	1.00	1.00	0.39	-0.27
T98	P&C	-0.03	-0.05	0.05	0.01
T98	Metal	0.00	0.00	0.00	0.00
T98	Plastic	-0.05	-0.02	0.05	0.05
T78	Organic	-0.19	-0.19	-0.08	0.05
T68	Glass	-0.01	0.00	0.00	0.00
T68	Metal	0.00	0.00	0.00	0.00
T1112	Metal	0.11	0.02	0.00	-0.06

Table 14: Sensitivity analysis for each given transfer coefficient

It can be observed that the performance of the central sorting facility has the biggest impact on each indicator. Like the discussion in section 6, the sorting of plastic and organic waste has shown to have the biggest influence on the indicators. One could also note that these fractions have a high impact on their individual recycling rate. In contrast to P&C and metal, these fractions do not have a back-up sorting process which explains their relevance for the individual recycling rate. The performance of the central sorting facility was concluded to be certain (Table 3). Only the performance of metal sorting was uncertain but this will have a negligible impact. Other transfer coefficients are also observed to have a minimal impact on the results. Given that the material layer only requires the input of a sample analysis and transfer coefficients, the results from the material layer are considered reliable.

Besides transfer coefficients, other parameters are necessary to calculate the energy efficiency and climate impact. Therefore, a sensitivity analysis was performed on the most important parameters used to calculate these indicators (Table 15). The thermal and electrical efficiency of the incineration plant has the biggest influence on the energy efficiency of the system. This data was obtained for the specific incineration plant used by RoAF, and will therefore strengthen the results. Downstream losses are in the model also sent to this incineration plant and thereby generating energy according to the technology observed at the Klemetsrud incineration plant. However, this may not be the case for losses in recycling processes happening in Europe. Including multiple incineration plants in the model could thus significantly change the energy efficiency presented in the results.

Climate impact

Parameter	Fraction	NSR
Avoided Emissions	P&C	-1.00
	Residual	-0.61
	Plastic	-0.29
	Metal	-0.23
	Glass	-0.18
	Organic	-0.14
Recycling Emissions	Glass	0.17
	P&C	0.69
Incineration Emissions	Rest	0.50
	Plastic	0.80
T29	Plastic	-0.45
Emission factor	Electricity	-0.04
	Diesel	0.10

Energy efficiency

Parameter	Fraction /type	NSR
T29	Plastic	-0.17
T27	Organic	0.07
T29	P&C	-0.05
T78	Organic	-0.01
Process energy	Process 2	-0.01
	Process 9 - P&C	-0.04
	Process 8	-0.01
	Process 9 - RW	-0.01
Energy generation	Methane yield	0.11
	Heat and power	1.00

Table 15: sensitivity analysis

The data used to calculate the avoided emissions has a significant impact on the result. A very high impact is observed for the avoided emission factor of P&C. The avoided (and recycling) emissions for paper and cardboard were developed to represent the Norwegian average (Raadal et al., 2009), hence it is considered to be representative for RoAF as well. Because one factor for both paper and cardboard is used in this case, changing the assumption of 50% paper and 50% cardboard could have a significant impact on the results.

The avoided emissions for residual waste are determined by the replaced district heating and electricity mix. Energy carriers used in a local district heating system can vary significantly from the Norwegian average used in this study. The assumption that oil and gas will be used to replace the share of waste in a district heating system will thus have a significant impact on the results. In addition, incineration plants in Europe will mostly likely replace more polluting energy sources which will increase the benefits from waste incineration and thus decrease the overall climate impact. As the avoided emissions from residual waste are based on the energy generation, a change in thermal and electrical efficiency will have the same impact on the climate indicator as the one from residual waste. Stressing the sensitivity from the incineration process once more.

Avoided emissions from plastic are also calculated to represent the Norwegian average (Raadal, Brekke, & Modahl, 2008). This includes the incineration of 36.6% that was sent to the various recycling plants. However, this is already included in the model and the avoided emissions for plastic recycling will therefore be underestimated. However, this will only have a minimal impact on the total results (Table 15). Finally, one could also observe a negligible impact from the emissions factors for diesel and electricity. Diesel and electricity is only used to calculate the impacts from transport and sorting processes. As these represent only 5% of the total generated emissions, a change in these factors will have a minimal impact. For other processes, the emission data is obtained from a database (Ecoinvent 2.2) that used the European power mix

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7.3 Future work

Including the effect from different collection technologies will result in more detailed guidelines for the waste companies. In this study, the performance of each collection technology was assumed to be equal (section 4.2.1). Therefore, the scenarios were developed by changing the collection efficiencies (section 5). However, this method does not answer the question of how these collection efficiencies will be reached. To analyse the impact from different collection technologies, a representative sample analysis of the waste generated by each collection technology should be available. Once this is available, it can easily be implemented in the model and scenarios can be developed by changing the collection technology. This will show the impact of a change in collection technology and will most likely highlight the importance of a change in human behaviour.

Adding an economic analysis to the model will facilitate a cost-benefit analysis. Currently, the model studies the performance of the system on three levels: a material, energy and emission level. This provides the user with a good overview on the sustainability criteria of the system but lacks to give an overview on the economic performance. The costs of a shift in collection technology could for example be compared with the economic benefits from a cleaner waste stream and thus increased recycling. Including an economic analysis in the model gives the user an overview on the feasibility of the measures given certain economic constraints. Furthermore, by analysing the revenue streams, the role of the producer responsibility organization will become visible. Maintaining a system perspective should be a key factor in the economic analysis. Implementing the 55% target for plastic packaging waste will result in less energy generation which is likely to change the business model of an incineration plant. However, reaching that target could also imply the construction of a sorting facility of increased employment in the transport and recycling sector. Because an inter-communal waste company is a public entity that has multiple roles in the society, it is important to maintain the holistic perspective.

A comparison between different cities using the same model allows to make more general conclusions. The model is currently only tested on one company which makes it hard to generalize. Using the same model for different cities will support comparison on an equal ground. Based on this, best practices could be derived to lift the performance of the entire Norwegian waste sector. Furthermore, the impact of implementing a central sorting facility will become visible. Because the central sorting facility is already implemented in the reference scenario, it is hard to analyse the true impact of a central sorting facility. Coupling this with an economic analysis will most likely identify a change in revenue flows from downstream actors to the waste company.

Finally, the model could be improved on different areas. First, increasing the level of detail to waste fractions on each layer will increase the quality of the results. The energy layer is currently based on data for each waste type. This implies that the same distance is used to transport plastic and paper from the sorting facility to its recycling plant. Distance, transport and process energy are currently given for each waste type and do not differentiate between waste fractions. Secondly, as colleting waste presents an important cost for the waste company, one should include the transport to and from each collection route. Thirdly, by adding the material replacement rates to the external markets, future developments in the production sector can be included which will generate better avoided emissions for future scenarios. The result from future scenarios could also be improved by including the effect from waste minimization programmes. Fourth, because the 65% target applies to household waste, the scope should be widened to include waste from recycling parks. In the case of RoAF, 45% of the total household waste is delivered to recycling parks and a recycling rate of 47% was reported for this share. As explained previously, reaching the 65% target based on collected waste will be challenging. Increasing the recycling rate of waste delivered to parks will thus be necessary to keep the chances on reaching the target.

8 Conclusions

The developed model has proved to be useful for analysing a complex and inter-connected waste management system. Based on material, energy and sustainability criteria, one can conclude that the collection of organic waste should be improved. Currently 44% of all organic waste is collected in the green bags which results in an organic recycling rate of 27%. As organic waste represents a large share of the total household waste, this will lead to significant improvements in the total recycling rate. Despite the implementation of a central sorting facility, the plastic recycling rate was found to be 32%. A low organic collection efficiency was identified as one of the main reasons for its deficient performance. Focusing on organic collection will therefore also increase plastic recycling, which secures significant climate benefits.

The waste management system is dependent on higher collection efficiencies to reach the circular economy targets. As the central sorting facility is mainly focused on sorting plastics, implementing a central sorting machine will not be enough to reach the 65% target. This highlights the importance of correct waste collection and the role of inter-communal waste companies. Reaching the 65% target was shown to be challenging and requires improvements in collection and sorting efficiencies for each waste fraction. This also underlines the need for waste minimization programmes and high recycling rates for recycling parks.

The 55% target for plastic packaging helps to ensure a high climate benefit. Significant improvements in the overall material recycling rate are obtained by focusing on the biggest waste fraction such as organic waste. However, the highest climate benefits are realized by focusing on the most polluting waste fractions like plastic. Therefore, a higher recycling rate does not necessarily lead to a higher climate benefit. Reaching the 55% target will secure significant climate benefits but will also lead to a lower energy efficiency. A reduction in energy generation from waste can be limited but not compensated by an increase in biogas production. The implementation of a central sorting facility can be seen as an effective strategy to increase plastic recycling. However, the benefits of a central sorting facility are dependent on the performance of each individual value chain.

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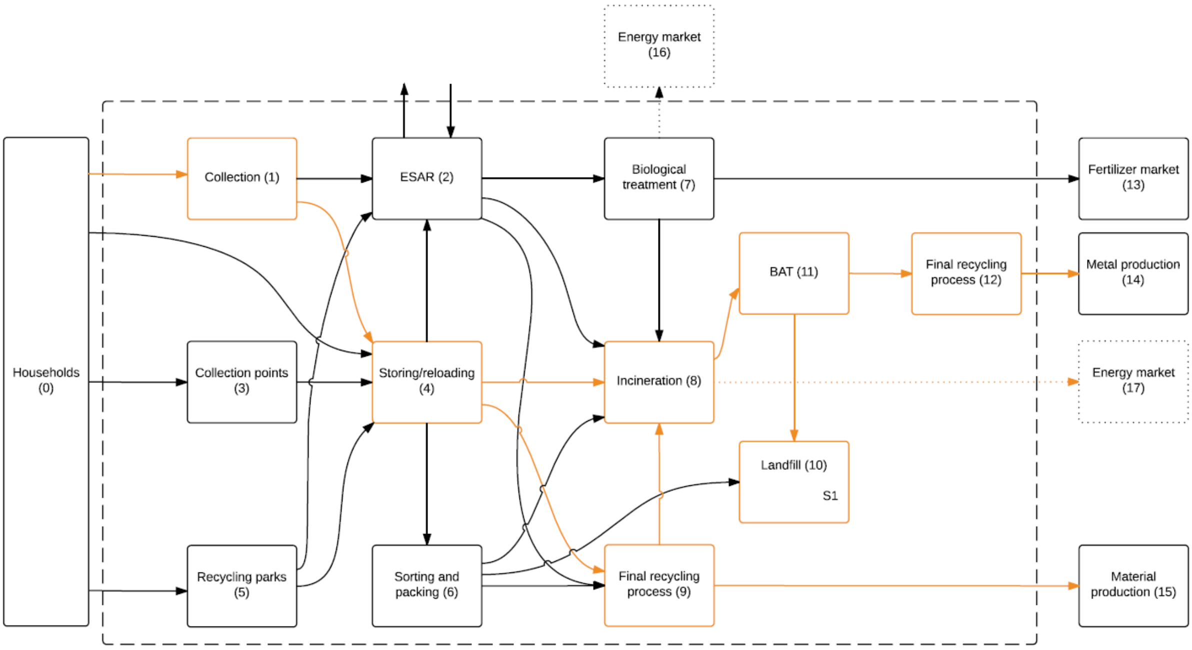
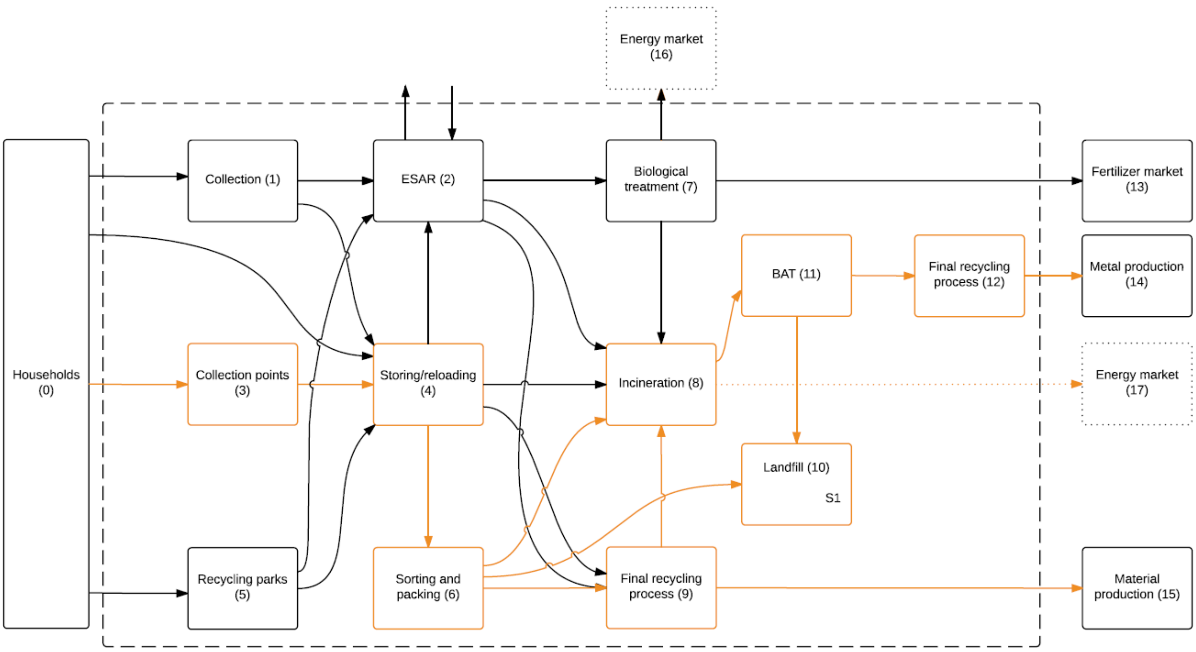
Appendices

A.1 Flow chart

Flowchart representing the value chain of P&C collected by RoAF



Flowchart representing the value chain of G&M collected by RoAF



A.2 Material layer

a. Input MATLAB

Flow XO1 – Flow composition (%)

Fraction	RW	PC	G&M	GB
Glass	0.034	0	0	0
Metal	0.023	0	0	0
Plastic	0.149	0.03	0	0
Organic	0.335	0	0	1
P&C	0.102	0.97	0	0
Rest	0.318	0	0	0
Hazardous	0.006	0	0	0
Textiles	0.033	0	0	0

Flow X01 – Technology distribution (%)

Technology	RW	PC	G&M	GB
Small bin	0.73	0.73	0	0.73
Container	0.15	0.15	0	0.15
Underground	0.11	0.13	0	0.11
Vacuum	0.02	0.00	0	0.02

Sources:

X01 – RW	(Syversen & Bjørnerud, 2016)
X01 – PC	(Lille-Schulstad, 2016)
X01 - GB	Assumption
Technology mix	(Syversen & Bjørnerud, 2015b) The share from vacuum systems was lowered with 2.2 pp after comparing the results with data from RoAF

Flow XO3 – Flow composition (%)

Fraction	RW	PC	G&M	GB
Glass	0	0	0.89	0
Metal	0	0	0.07	0
Plastic	0	0	0	0
Organic	0	0	0	0
P&C	0	0	0	0
Rest	0	0	0.04	0
Hazardous	0	0	0	0
Textiles	0	0	0	0

Flow X03 – Technology distribution (%)

Technology	RW	PC	G&M	GB
Small bin	0	0	0	0
Container	0	0	1	0
Underground	0	0	0	0
Vacuum	0	0	0	0

Sources:

X01 – GM	(Solberg, 2016)
Technology mix	(Rem, 2016) containers represent collection points in this case

Flow XO4 – Flow composition (%)

Fraction	RW	PC	G&M	GB
Glass	0.039	0	0	0
Metal	0.028	0	0	0
Plastic	0.169	0.03	0	0
Organic	0.292	0	0	1
P&C	0.116	0.97	0	0
Rest	0.323	0	0	0
Hazardous	0.014	0	0	0
Textiles	0.019	0	0	0

Flow X04 – Technology distribution (%)

Technology	RW	PC	G&M	GB
Small bin	0.94	0.94	0	0.94
Container	0.04	0.04	0	0.04
Underground	0.02	0.02	0	0.02
Vacuum	0.00	0.00	0	0.00

Sources:
X01 – RW, Technology mix (Syversen & Bjørnerud, 2015a)
X01 – PC (Lille-Schulstad, 2016)

Size of the flows in 2016

In tonnes	RW	PC	G&M	GB
X01	27451	8272	0	7474
X03	0	0	2166	0
X04	2705	853	0	419
Total	30156	9125	2166	7893

Sources:
X01, X04: RW + GB (Henie, 2017)
Share RW X01 (Syversen & Bjørnerud, 2016)
Share RW X04 (Syversen & Bjørnerud, 2015a)
PC, GM (Henie, 2017)

Overview of the transfer coefficients

TC	T811	T78	T610	T69	T48	T1112	T98	
Type	All	RW	GM	GM	PC	All	PC	RW
Glass	0.97	0	0	0.99	0	0	0	0
Metal	0.94	0	0	0.99	0	0.985	0	0.04
Plastic	0.018	0	0	0	1	0	0	0.05
Organic	0.133	0	0	0	0	0	0	1
P&C	0.56	0	0	0	0	0	0.025	0.025
Rest	0.102	1	0.61	0	0	0	1	1
Hazardous	0.1	0	0	0	0	0	0	0
Textiles	0.04	0	0	0	0	0	0	0

Sources:

T811	(Christensen, 2011)
T78	(Reistad, 2017)
T610, T69	(Solberg, 2016)
T48, T98 - PC	(Lille-Schulstad, 2016)
T98 - RW	See calculation in appendix A.2b
T1112	Assumption

Transfer coefficients from the biogas plant

Calculation of the transfer coefficients

Name	Symbol	Weight (t)	Share	Source/formula
Organic waste	OW,in	5965	1.00	(Syversen & Bjørnerud, 2016)
Biogas out	BG,out	3365	0.56	(Reistad, 2017)
Biorest out	GR,out	1641	0.28	GR,out = S,DM + L,DM
Solid (DM)	S,DM	1619		(Reistad, 2017)
Liquid (DM)	L,DM	22		(Reistad, 2017)
Reject out	R,out	960	0.16	R,out = OW,in – BG,out – GB,out

Overview of the transfer coefficients for the biogas plant

TC	T78	T713
Glass	0	0
Metal	0	0
Plastic	0	0
Organic	0.16	0.28
P&C	0	0
Rest	0	0
Hazardous	0	0
Textiles	0	0

b. Central sorting

Inflow and outflow of the central sorting facility

	Area 1,2 and 3		Area 4			
	Share	Weight (t)	Share	Weight (t)	In (t)	OUT (t)
Total	100%	35409	100%	3124	38533	38533
Green bags	21%	7578	13%	419	7996	5965
Glass	3%	946	3%	106	1052	0
Metal	2%	640	2%	76	716	714
Plastic	12%	4147	15%	457	4604	1745
Organic	26%	9324	25%	790	10114	0
P&C	8%	2839	10%	314	3153	1292
Rest	25%	8850	28%	874	9724	28638
Hazardous	0%	167	1%	38	205	0
Textiles	3%	918	2%	51	970	0

Sources:

Input Area 1,2 and 3	(Syversen & Bjørnerud, 2016)
Input Area 4	(Syversen & Bjørnerud, 2015a)
Output	(RoAF, 2016)

Calculation of the flows that lead to the transfer coefficients presented in Error! Reference source not found.

	IN (t)	OUT (t)	Purity	Flows (t) X27	X28	X29	X20
Total	38533	38533		5965	28638	3751	180
Green bags	7996	5965	96%	5727	2270	0	0
Glass	1052	0		0	1052	0	0
Metal	716	714	85%	0	82	633	0
Plastic	4604	1745	90%	0	2946	1658	0
Organic	10114	0		0	9766	168	180
P&C	3153	1292	100%	0	1861	1292	0
Residual	9724	28638		239	9486	0	0
Hazardous	205	0		0	205	0	0
Textiles	970	0		0	970	0	0
Vapour		180					

Name	Symbol	Value	Source/formula
Flow X27	X27	5727	X27 = O,gb * P,gb
Flow X29 - Metal	X29,m	633	X29,m = O,m * P,m + O,m * (1-P,m) * (1-DMO)
Flow X29 – Plastic	X29,pl	1658	X29,pl = O,pl * P,pl + O,pl * (1-P,pl) * (1-DPO)
Flow X29 - Residual	X29,r	168	X29,r = O,m * (1-P,m) * DMO + O,pl * (1-P,pl) * DPO
TC 98 - Metal	T98,m	4%	T98,m = (1-P,m) * (1-DMO)
TC 98 - Plastic	T98,p	5%	T98,p = (1-P,p) * (1-DPO)
Flow X20 - Organic	X20,org	180	(RoAF, 2016)
Purity plastic	P,pl	90%	(Skovly, 2017)
Purity Metal	P,m	85%	(Skovly, 2017)
Purity Green bags	P,gb	96%	(Skovly, 2017)
Dirty plastic in Organic	DPO	50%	(Syversen & Bjørnerud, 2016)
Dirty metal in Organic	DMO	75%	(Syversen & Bjørnerud, 2016)
Outflow green bags	O,gb	5965	(RoAF, 2016)
Outflow plastic	O,pl	1745	(RoAF, 2016)

c. Indicators

The vectors containing the processes used to calculate the indicators presented in section 4.2.1.

Vector	Process number
a	[1, 3, 5]
b	[7, 9]
c	[13, 14, 15]
d	[16]
e – RW, GB	[7, 9]
e – P&C	[4]
e – G&M	[6]

A.3 Energy layer

a. Transport Energy

Formula used to calculate the Energy consumption from waste collection (Equation 6)

for a given fuel type (f), collection technology (t) and waste type (i)

$$Energy\ consumption_{f,t,i}\ \left(\frac{kwh}{yr}\right) = Energy\ requirement_{f,t,i}\left(\frac{l}{yr}\right) * energy\ content_{f}\ \left(\frac{kwh}{l}\right)$$

$$Energy\ requirement_{f,t,i}\ \left(\frac{kwh}{yr}\right) = route\ distance_{f,t,i}\ \left(\frac{km}{route}\right) * collection\ frequency_{t,i}\ \left(\frac{route}{yr}\right) * Fuel\ consumption_{f}\ \left(\frac{l}{km}\right)$$

Data used to calculate the energy requirement, consumption and energy intensity

Small bins and containers are collected at the same time by the same vehicle, the result will thus be equal for these collection technologies. The same accounts for GB and RW

Collection frequency (route/yr)	RW	PC
Small bins	52	13
Container	52	13
Underground	52	26
Vacuum system	52	0

Source: (Henie, 2017)

	Fuel consumption		Energy content	
Biogas	0.6	Nm3/km	6.5	Kwh/Nm3
Diesel	0.4	l/km	11.9	Kwh/l

Source:

Fuel consumption Biogas	(Holm, 2017)
Fuel consumption Diesel	(Bakken, 2016)
Energy content Biogas	(Baltic Biogas Bus Project, n.d.)
Energy content Diesel	(Schmied et al., 2012)

Area 1	Route distance (km)		Collection technology		Fuel type		Energy requirement (l/yr , Nm3/yr)	
Car	RW	PC	RW	PC	RW	PC	RW	PC
1	386	386	Small bins	Small bins	Diesel	Diesel	8029	2007
2	307	307	Small bins	Small bins	Biogas	Biogas	9578	2395
3	311	311	Small bins	Small bins	Biogas	Biogas	9703	2426
4	251	251	Small bins	Small bins	Biogas	Biogas	7831	1958
5	264	264	Small bins	Small bins	Biogas	Biogas	8237	2059
6	418	418	Underground	Underground	Biogas	Biogas	13042	6521

Source: (Henie, 2017), formula for energy requirement

Area 1	Weight (t/yr)		Energy intensity (Kwh/tkm)	
Car	RW	PC	RW	PC
1	463	239	0.533	0.258
2	1335	239	0.152	0.212
3	1335	239	0.152	0.212
4	1335	239	0.152	0.212
5	1335	239	0.152	0.212
6	1381	576	0.147	0.176

Source:

Energy intensity	Equation 6
Weight car 1,6	(Skovly, 2017)
Weight other cars	A equal division between the cars was assumed based on the total weight given by (Skovly, 2017)

Area 2	Route distance (km)		Collection technology		Fuel type		Energy requirement (l/yr , Nm3/yr)	
Car	RW	PC	RW	PC	RW	PC	RW	PC
1	627	627	Small bins	Small bins	Biogas	Biogas	19562	4891
2	520	520	Small bins	Small bins	Biogas	Biogas	16224	4056
3	531	531	Small bins	Small bins	Biogas	Biogas	16567	4142
4	382	382	Small bins	Small bins	Biogas	Biogas	11918	2980
5	294	294	Small bins	Small bins	Biogas	Biogas	9173	2293
6	364	364	Small bins	Small bins	Biogas	Biogas	11357	2839
7	594	594	Small bins	Small bins	Biogas	Biogas	18533	4633

Source: (Henie, 2017), formula for energy requirement

Area 2	Weight (t/yr)		Energy intensity (Kwh/tkm)	
Car	RW	PC	RW	PC
1	1839	405	0.110	0.125
2	1839	405	0.110	0.125
3	1839	405	0.110	0.125
4	1839	405	0.110	0.125
5	1839	405	0.110	0.125
6	1839	405	0.110	0.125
7	1839	405	0.110	0.125

Source:

Energy intensity	Equation 6
Weight	A equal division between the cars was assumed based on the total weight given by (Skovly, 2017)

Area 3	Route distance (km)		Collection technology		Fuel type		Energy requirement (l/yr , Nm3/yr)	
Car	RW	PC	RW	PC	RW	PC	RW	PC
1	395	395	Small bins	Small bins	Biogas	Biogas	12324	3081
2	329	329	Small bins	Small bins	Biogas	Biogas	10265	2566
3	142	142	Small bins	Small bins	Diesel	Diesel	2954	738
4	264	264	Small bins	Small bins	Biogas	Biogas	8237	2059
5	253	253	Small bins	Small bins	Biogas	Biogas	7894	1973
6	243	243	Small bins	Small bins	Biogas	Biogas	7582	1895
7	258	258	Small bins	Small bins	Biogas	Biogas	8050	2012

Source: (Henie, 2017), formula for energy requirement

Area 3	Weight (t/yr)		Energy intensity (Kwh/tkm)	
Car	RW	PC	RW	PC
1	2124	524	0.095	0.097
2	2124	524	0.095	0.097
3	2124	524	0.116	0.118
4	2124	524	0.095	0.097
5	2124	524	0.095	0.097
6	2124	524	0.095	0.097
7	2124	524	0.095	0.097

Source:

Energy intensity	Equation 6
Weight	A equal division between the cars was assumed based on the total weight given by (Skovly, 2017), separate data on car 3 was obtained

Area 4	Route distance (km)		Collection technology		Fuel type		Energy requirement (l/yr , Nm3/yr)	
Car	RW	PC	RW	PC	RW	PC	RW	PC
1	276.5	276.5	Small bins	Small bins	Diesel	Diesel	5751	1438
2	276.5	276.5	Small bins	Small bins	Diesel	Diesel	5751	1438
3	276.5	276.5	Small bins	Small bins	Diesel	Diesel	5751	1438
4	276.5	276.5	Small bins	Small bins	Diesel	Diesel	5751	1438

Source:

Route distance	An equal division between the routes was assumed based on the yearly amount of km given by (Rem, 2016)
Rest of the table	(Henie, 2017)

Area 4	Weight (t/yr)		Energy intensity (Kwh/tkm)	
Car	RW	PC	RW	PC
1	781	213	0.316	0.289
2	781	213	0.316	0.289
3	781	213	0.316	0.289
4	781	213	0.316	0.289

Source:

Energy intensity	Equation 6
Weight	A equal division between the cars was assumed based on the total weight given by (Skovly, 2017)

RoAF	Route distance (km)		Collection technology		Fuel type		Energy requirement (l/yr , Nm3/yr)	
Car	RW	PC	RW	PC	RW	PC	RW	PC
1	50	50	Vacuum		Diesel		1040	
2	380	380	Underground	Underground	Diesel	Diesel	7904	3952
3	120	120	Underground	Underground	Diesel	Diesel	2496	1248

Source: (Henie, 2017)

Due to a low amount of PC collected with a vacuum system, the vacuum system was assumed to only collection residual waste

RoAF	Weight (t/yr)		Energy intensity (Kwh/tkm)	
Car	RW	PC	RW	PC
1	575	0	0.429	0.000
2	1772	301	0.139	0.411
3	1772	301	0.139	0.411

Source: (Henie, 2017)

The average energy intensities for each technology and fuel type

Based on the data presented above (used as an input for the model)

X01		RW		PC	
Technology	Fuel	%	Kwh/tkm	%	Kwh/tkm
Small bins	Diesel	1%	0.324	1%	0.188
	Biogas	85%	0.115	83%	0.136
Container	Diesel	1%	0.324	1%	0.188
	Biogas	85%	0.115	83%	0.136
Underground	Diesel	39%	0.139	28%	0.411
	Biogas	13%	0.147	22%	0.176
Vacuum	Diesel	100%	0.429	0%	0.000
	Biogas	0%	0.000	0%	0.000

X04		RW		PC	
Technology	Fuel	%	Kwh/tkm	%	Kwh/tkm
Small bins	Diesel	100%	0.316	100%	0.289
	Biogas	0%	0.000	0%	0.000
Container	Diesel	100%	0.316	100%	0.289
	Biogas	0%	0.000	0%	0.000
Underground	Diesel	100%	0.139	100%	0.411
	Biogas	0%	0.000	0%	0.000

The Fuel divisions are based on the km driven and weight collected by each fuel type and technology

		Km driven		Weight collected	
Technology	Fuel	RW	PC	RW	PC
Small bins	Diesel	8%	8%	8%	10%
	Biogas	92%	92%	92%	90%
Underground	Diesel	54%	54%	72%	51%
	Biogas	46%	46%	28%	49%
Vacuum	Diesel	100%	0%	100%	0%
	Biogas	0%	0%	0%	0%

Average distance of a collection route per waste type and collection technology (km)

Based on the data presented above (used as an input for the model)

	X01		X04	
Waste type	RW	PC	RW	PC
Small bins	353	353	276.5	276.5
Container	353	353	276.5	276.5
Underground	306	306	250	250
Vacuum	50	50		

G&M collection

Car nr.	Distance (km)	Technology	Fuel	Energy req. (l/yr)	Weight (t/yr)	Enenrgy int. (kwh/tkm
1	500	Container	Diesel	10400	2166	0.114

Source: weight: (Henie, 2017) , distance: assumption

Downstream transport

Type truck (max load)	Energy intensity (Kwh/tkm)
7.5t	0.925
12t	0.724
24t	0.427
40t	0.273

Source: (Schmied et al., 2012)

Based on the maximum load of the trucks leaving RoAF, it was decided to use a 40t truck when more than 800t per year was transported. A lower amount was transported using a 24t truck.

b. Process energy

Process energy

Process	Electricity (kwh/t)	Diesel (kwh/t)	Heat (kwh/t)	Oil (kwh/t)	Source
2	43	2	7	0	(RoAF, 2016)
4	15	0	0	0	Assumption
6	18	0	0	0	(Solberg, 2016)
7	80	0	0	0	(Reistad, 2017)
8	117	0	0	25	(Norling, 2017)
11	10	0	0	0	Assumption

As the process energy cannot be defined for each waste fraction, the process energy for a plastic recycling plant was used to represent the process energy necessary to recycle the different fraction sent from the sorting facilty. Data from the recycling processes is obtained from Ecoinvent 2.2

			Electricity	NG	HFO
Process 9 - G&M			221.1	92.1	0.5
	0.9	Glass	244.0	99.2	0.0
	0.1	Metal	15.4	28.3	4.6
Process 9 - RW		Plastic	660.0	166.9	0.0
Process 9 - PC			65.2	1243.1	0.0
	0.5	Cardboard	88.4	66.8	0.0
	0.5	Paper	42.0	2419.4	0.0
Process 12		Metal	15.4	28.3	4.6

Energy efficiency

Facility	Factor	Source
Klemetsrud AS	82% (18% Electrical, 64% Thermal)	(Norling, 2017)
HRA	160 Nm3/t organic waste	(Reistad, 2017)

c. Feedstock Energy

Feedstock energy used in the model

Fraction	LHV (KJ/kg)
Glass	-73
Metal	-147
Plastic	20144
Organic	1912
P&C	6440
Residual	7650
Hazardous	7650
Textiles	11789

Sources: (Christensen, 2011)

The LHV of residual and hazardous waste is assumed to be the average of the other fractions.

A.4 Emissions layer

District heating

In the avoided district heating mix, the 30% decrease in waste incineration is replaced by an 15% increase for both gas and heavy fuel oils

	Current Mix	g CO2e./kwh	Avoided mix	g CO2e./kwh
Gass-/dieseloljer	1%	298	16%	298
Bark, flis og tre	28%	16	28%	16
Biooljer	1%	10	1%	10
Avfall	50%	211	20%	211
Elektrisitet	13%	110	13%	110
Spillvarme	2%	0	2%	0
Gass	4%	264	19%	264
Total		139		160

Sources:

Emissions factors	(Løseth, 2011)
Emissions from waste	(Lien, 2013)
Current mix	(SSB, 2016)

Avoided emissions from the incineration of residual waste

Name	Symbol	Value	Source/Formula
Avoided emissions	AE,rest	0.135	AE,rest = El,no*E,e + DH*E,t
Electricity (NO)	El,no	0.044	Ecoinvent 2.2
District Heating	DH	0.139	Presented above
Thermal efficiency	E,t	64%	Presented above
Electrical efficiency	E,e	18%	Presented above

A.5 Scenarios

Quantification of flows under the reference scenario

t/capita Flow	RW	PC	G&M	GB
X01	0.15	0.05	0.00	0.04
X03	0.00	0.00	0.011	0.00
X04	0.17	0.05	0.00	0.03

a. G&M collection

Quantification of the flows

Flows	Inhabitants	RW	PC	G&M	GB
X01	194969	28714	9021	3403	8151
X03	212769	0	0	0	0
X04	17800	2887	949	311	466

Flow XO1 – Flow composition (%)

Fraction	RW	PC	G&M	GB
Glass	0.00	0	0.74	0
Metal	0.00	0	0.24	0
Plastic	0.16	0.03	0.00	0
Organic	0.35	0	0.00	1
P&C	0.11	0.97	0.00	0
Rest	0.34	0	0.02	0
Hazardous	0.01	0	0.00	0
Textiles	0.03	0	0.00	0

Flow X01 – Technology distribution (%)

Technology	RW	PC	G&M	GB
Small bin	0.73	0.73	0.73	0.73
Container	0.15	0.15	0.15	0.15
Underground	0.11	0.13	0.13	0.11
Vacuum	0.02	0.00	0.00	0.02

Note that only the composition of small bins is changed to increase the collection efficiency. The other collection technologies remain unchanged compared to the reference scenario.

Flow XO4 – Flow composition (%)

Fraction	RW	PC	G&M	GB
Glass	0.01	0	0.78	0
Metal	0.01	0	0.20	0
Plastic	0.16	0.03	0.00	0
Organic	0.35	0	0.00	1
P&C	0.11	0.97	0.00	0
Rest	0.33	0	0.02	0
Hazardous	0.01	0	0.00	0
Textiles	0.03	0	0.00	0

Flow X04 – Technology distribution (%)

Technology	RW	PC	G&M	GB
Small bin	0.94	0.94	0.94	0.94
Container	0.04	0.04	0.04	0.04
Underground	0.02	0.02	0.02	0.02
Vacuum	0.00	0.00	0.00	0.00

Transport energy for the collection of GM

Collection frequency (route/yr)	GM
Small bins	5.2
Container	5.2
Underground	26
Vacuum system	0

Car nr.	Distance	Technology	Fuel type	Energy Requirement	Weight (t)	Kwh/tkm
Area 1						
2	760	Small bins	Biogas	2370	306	0.066
3	760	Small bins	Biogas	2370	306	0.066
6	418	Underground	Biogas	6521	106	0.954
Area 2						
1	828	Small bins	Biogas	2583	274	0.074
2	828	Small bins	Biogas	2583	274	0.074
3	828	Small bins	Biogas	2583	274	0.074
4	828	Small bins	Biogas	2583	274	0.074
Area 3						
1	628	Small bins	Biogas	1959	423	0.048
2	628	Small bins	Biogas	1959	423	0.048
4	628	Small bins	Biogas	1959	423	0.048
Roaf						
2	500	Underground	Diesel	5200	324	0.380
Area 4						
1	1106	Small bins	Diesel	2300	306	0.081

The total weight for small bins in X01 is divided over the different areas using the division that was observed for RW. (Area1: 21%, Area 2: 37%, Area 3: 43%). 13% of the GM in X01 was collected with underground bins. 25% of this was assumed to be collected in area 1, 75% with RoAF cars. 2% of the GM in X04 was collected with underground bins, this was added to the weight collected by RoAF.

Average energy intensities based on the data presented above

		X01		X04	
Technology	Fuel	%	Kwh/tkm	%	Kwh/tkm
Small bins	Diesel	0%	0.000	100%	0.081
	Biogas	100%	0.064	0%	0.000
Container	Diesel	0%	0.000	100%	0.081
	Biogas	100%	0.064	0%	0.000
Underground	Diesel	41%	0.380	100%	0.380
	Biogas	11%	0.954	0%	0.000
Vacuum	Diesel	0%	0.000		
	Biogas	0%	0.000		

Data for fuel division and average route distance is based on the route data presented above.

		Fuel division		Km route	
Technology	Fuel	Km	Weight	X01	X04
Small bins	Diesel	0%	0%	746	1106
	Biogas	100%	100%		
Underground	Diesel	54%	75%	459	500
	Biogas	46%	25%		
Vacuum	Diesel	0%	0%	0	0
	Biogas	0%	0%		

As containers and small bins are collected at the same time, the same factors are used for this.

b. Organic bin

Quantification of the flows

Flow	Inhabitants	RW	PC	G&M	GB
X01	194969	23639	9021	0	14450
X03	212769	0	0	2366	0
X04	17800	2306	949	0	1170

Flow XO1 – Flow composition (%)

Fraction	RW	PC	G&M	GB
Glass	0.05	0	0.74	0
Metal	0.03	0	0.24	0
Plastic	0.21	0.03	0.00	0
Organic	0.10	0	0.00	1
P&C	0.14	0.97	0.00	0
Rest	0.44	0	0.02	0
Hazardous	0.01	0	0.00	0
Textiles	0.04	0	0.00	0

Flow X01 – Technology distribution (%)

Technology	RW	PC	G&M	GB
Small bin	0.73	0.73	0	0.73
Container	0.15	0.15	0	0
Underground	0.11	0.13	0	0.28
Vacuum	0.02	0.00	0	0

Flow XO4 – Flow composition (%)

Fraction	RW	PC	G&M	GB
Glass	0.04	0	0.78	0
Metal	0.03	0	0.20	0
Plastic	0.19	0.03	0.00	0
Organic	0.14	0	0.00	1
P&C	0.13	0.97	0.00	0
Rest	0.41	0	0.02	0
Hazardous	0.01	0	0.00	0
Textiles	0.04	0	0.00	0

Flow X04 – Technology distribution (%)

Technology	RW	PC	G&M	GB
Small bin	0.94	0.94	0	0.94
Container	0.04	0.04	0	0
Underground	0.02	0.02	0	0.06
Vacuum	0.00	0.00	0	0

Transport Energy for the collection of organic bins

Collection frequency (route/yr)	GM
Small bins	26
Container	26
Underground	26
Vacuum system	0

Car nr.	Distance	Technology	Fuel type	Energy Requirement (l/yr , Nm3/yr)	Weight (t)	Kwh/tkm
Area 1						
1	386	Small bins	Diesel	4014	485	0.254
2	307	Small bins	Biogas	4789	485	0.209
3	311	Small bins	Biogas	4852	485	0.209
4	251	Small bins	Biogas	3916	485	0.209
5	264	Small bins	Biogas	4118	485	0.209
6	418	Underground	Biogas	6521	1118	0.091
Area 2						
1	627	Small bins	Biogas	9781	621	0.163
2	520	Small bins	Biogas	8112	621	0.163
3	531	Small bins	Biogas	8284	621	0.163
4	382	Small bins	Biogas	5959	621	0.163
5	294	Small bins	Biogas	4586	621	0.163
6	364	Small bins	Biogas	5678	621	0.163
7	594	Small bins	Biogas	9266	621	0.163
Area 3						
1	395	Small bins	Biogas	6162	717	0.141
2	329	Small bins	Biogas	5132	717	0.141
3	142	Small bins	Diesel	1477	717	0.172
4	264	Small bins	Biogas	4118	717	0.141
5	253	Small bins	Biogas	3947	717	0.141
6	243	Small bins	Biogas	3791	717	0.141
7	258	Small bins	Biogas	4025	717	0.141
Roaf						
1	50	Vacuum	Diesel	0	0	0.000
2	380	Underground	Diesel	3952	1717	0.072
3	120	Underground	Diesel	1248	1717	0.072
Area 4						
1	276.5	Small bins	Diesel	2876	309	0.400
	276.5	Small bins	Diesel	2876	309	0.400
	276.5	Small bins	Diesel	2876	309	0.400
	276.5	Small bins	Diesel	2876	309	0.400

The weight was divided over the different areas following the same method explained in the GM collection scenario

The average energy requirement becomes

		X01		X04	
Technology	Fuel	%	Kwh/tkm	%	Kwh/tkm
Small bins	Diesel	1%	0.213	100%	0.400
	Biogas	83%	0.166	0%	0.000
Container	Diesel	1%	0.213	100%	0.400
	Biogas	83%	0.166	0%	0.000
Underground	Diesel	41%	0.072	100%	0.072
	Biogas	11%	0.091	0%	0.000
Vacuum	Diesel	0%	0.000		
	Biogas	0%	0.000		

The fuel division and average distance for a route are

		Fuel division		Km route	
Technology	Fuel	Km	Weight	X01	X04
Small bins	Diesel	8%	8%	353	276.5
	Biogas	92%	92%		
Underground	Diesel	54%	54%	306	250
	Biogas	46%	46%		
Vacuum	Diesel	100%	100%	50	
	Biogas	0%	0%		

c. Perfect Collection

Quantification of the flows

Flows	Inhabitants	RW	PC	G&M	GB
X01	215969	17386	13281	4249	19803
X03	236769	0	0	0	0
X04	20800	1674	1279	409	1907

Flow XO1 – Flow composition (%)

Fraction	RW	PC	G&M	GB
Glass	0.00	0	0.77	0
Metal	0.00	0	0.23	0
Plastic	0.31	0	0.00	0
Organic	0.00	0	0.00	1
P&C	0.00	1	0.00	0
Rest	0.62	0	0.00	0
Hazardous	0.01	0	0.00	0
Textiles	0.06	0	0.00	0

Flow X01 – Technology distribution (%)

Technology	RW	PC	G&M	GB
Small bin	0.73	0.73	0.73	0.73
Container	0.15	0.15	0.15	0
Underground	0.11	0.13	0.13	0.28
Vacuum	0.02	0.00	0.00	0

Flow XO4 – Flow composition (%)

Fraction	RW	PC	G&M	GB
Glass	0.00	0	0.77	0
Metal	0.00	0	0.23	0
Plastic	0.31	0	0.00	0
Organic	0.00	0	0.00	1
P&C	0.00	1	0.00	0
Rest	0.62	0	0.00	0
Hazardous	0.01	0	0.00	0
Textiles	0.06	0	0.00	0

Flow X04 – Technology distribution (%)

Technology	RW	PC	G&M	GB
Small bin	0.94	0.94	0.94	0.94
Container	0.04	0.04	0.04	0
Underground	0.02	0.02	0.02	0.06
Vacuum	0.00	0.00	0.00	0

In contrast to the other scenarios, this flow composition is used for each collection technology. The transport requirements from both the GM collection and Organic bin scenario are used.

d. Perfect SAR

TC used in the Perfect SAR scenario

	T27	T28	T29	T20
Green bags	1.00	0.00	0.00	0.00
Glass	0.00	1.00	0.00	0.00
Metal	0.00	0.00	1.00	0.00
Plastic	0.00	0.20	0.80	0.00
Organic	0.00	0.98	0.00	0.02
P&C	0.00	0.00	1.00	0.00
Rest	0.00	1.00	0.00	0.00
Hazardous	0.00	1.00	0.00	0.00
Textiles	0.00	1.00	0.00	0.00

e. More GB

Quantification of the flows for 2022

Flows	Inhabitants	RW	PC	G&M	GB
X01	194969	26028	9021	3403	10838
X03	212769	0	0	0	0
X04	17800	2475	949	311	877

Flow XO1 – Flow composition (%)

Fraction	RW	PC	G&M	GB
Glass	0.00	0	0.74	0
Metal	0.00	0	0.24	0
Plastic	0.18	0.03	0.00	0
Organic	0.25	0	0.00	1
P&C	0.13	0.97	0.00	0
Rest	0.39	0	0.02	0
Hazardous	0.01	0	0.00	0
Textiles	0.04	0	0.00	0

Flow X01 – Technology distribution (%)

Technology	RW	PC	G&M	GB
Small bin	0.73	0.73	0.73	0.73
Container	0.15	0.15	0.15	0.15
Underground	0.11	0.13	0.13	0.11
Vacuum	0.02	0.00	0.00	0.02

Flow XO4 – Flow composition (%)

Fraction	RW	PC	G&M	GB
Glass	0.01	0	0.78	0
Metal	0.01	0	0.20	0
Plastic	0.17	0.03	0.00	0
Organic	0.27	0	0.00	1
P&C	0.12	0.97	0.00	0
Rest	0.37	0	0.02	0
Hazardous	0.01	0	0.00	0
Textiles	0.04	0	0.00	0

Flow X04 – Technology distribution (%)

Technology	RW	PC	G&M	GB
Small bin	0.94	0.94	0.94	0.94
Container	0.04	0.04	0.04	0.04
Underground	0.02	0.02	0.02	0.02
Vacuum	0.00	0.00	0.00	0.00

Quantification of the flows for 2030

Flows	Inhabitants	RW	PC	G&M	GB
X01	215969	25833	9993	3772	15002
X02	130626	0	0	0	0
X03	236769	0	0	0	0
X04	20800	2636	1109	363	1281

Flow XO1 – Flow composition (%)

Fraction	RW	PC	G&M	GB
Glass	0.00	0	0.74	0
Metal	0.00	0	0.24	0
Plastic	0.21	0.03	0.00	0
Organic	0.14	0	0.00	1
P&C	0.14	0.97	0.00	0
Rest	0.45	0	0.02	0
Hazardous	0.01	0	0.00	0
Textiles	0.04	0	0.00	0

Flow X01 – Technology distribution (%)

Technology	RW	PC	G&M	GB
Small bin	0.73	0.73	0.73	0.73
Container	0.15	0.15	0.15	0.15
Underground	0.11	0.13	0.13	0.11
Vacuum	0.02	0.00	0.00	0.02

Flow XO4 – Flow composition (%)

Fraction	RW	PC	G&M	GB
Glass	0.01	0	0.78	0
Metal	0.01	0	0.20	0
Plastic	0.20	0.03	0.00	0
Organic	0.18	0	0.00	1
P&C	0.13	0.97	0.00	0
Rest	0.42	0	0.02	0
Hazardous	0.01	0	0.00	0
Textiles	0.04	0	0.00	0

Flow X04 – Technology distribution (%)

Technology	RW	PC	G&M	GB
Small bin	0.94	0.94	0.94	0.94
Container	0.04	0.04	0.04	0.04
Underground	0.02	0.02	0.02	0.02
Vacuum	0.00	0.00	0.00	0.00

A.6 Results

a. Reference scenario 2016

Amount of each waste type being generated, sorted, material recycled and incinerated

Data is given in tonnes according the formula presented in section 4.2.1.

	Generated	Sorted	Recycled	Incinerated
Total	49340	20270	18936	30275
Glass	2962	1904	1904	1058
Metal	867	784	859	106
Plastic	4821	1637	1556	3266
Organic	17879	5818	4743	12958
P&C	11965	10127	9874	2091
Rest	9686	0	0	9636
Hazardous	203	0	0	203
Textiles	957	0	0	957

Overview of the destination of the generated amount of waste

biogas is attributed to energy recovery, bio residuals form the process are included in material recycling

Destination	tonnes	share
Waste generated	49340	100%
Energy recovery	28342	57%
Material recycling	15748	32%
Landfill	5073	10%
Vapour	177	0%

Overview of the energy inputs and generation

Data is given in kwh

Energy efficiency	15%
Feedstock	2.95E+08
Transport	4.95E+06
Process	2.22E+07
Out	4.83E+07

b. Scenarios for 2022

G&M Collection

Amount of each waste type being generated, sorted, material recycled and incinerated (tonnes) according the formula presented in section 4.2.1.

	Generated	Sorted	Recycled	Incinerated
Total	53902	23004	21495	32197
Glass	3236	2883	2883	353
Metal	948	913	945	42
Plastic	5269	1789	1700	3569
Organic	19525	6352	5179	14153
P&C	13074	11066	10789	2285
Rest	10583	0	0	10528
Hazardous	222	0	0	222
Textiles	1045	0	0	1045

Overview of the destination of the generated amount of waste, biogas is attributed to energy recovery, bio residuals form the process are included in material recycling

Destination	tonnes	share
Waste generated	53902	100%
Energy recovery	30932	57%
Material recycling	18015	33%
Landfill	4762	9%
Vapour	194	0%

Overview of the generated and avoided emissions caused by the pathways of each fraction. Data is given in Kg CO2e./inhabitants.

	Generated emissions		Avoided emissions		
Fraction	Recycling	Incineration	Energy	Material	Net impact
Glass	12	0	0	-12	0
Metal	0	0	0	-11	-11
Plastic	5	39	-10	-14	20
Organic	0	2	-11	0	-9
P&C	34	0	-2	-49	-17
Rest	0	25	-14	0	11

Organic bin

Amount of each waste type being generated, sorted, material recycled and incinerated (tonnes) according the formula presented in section 4.2.1.

	Generated	Sorted	Recycled	Incinerated
Total	53902	31477	28615	25270
Glass	3236	2080	2080	1156
Metal	948	857	939	116
Plastic	5269	1789	1700	3569
Organic	19525	15685	13108	6348
P&C	13074	11066	10789	2285
Rest	10583	0	0	10528
Hazardous	222	0	0	222
Textiles	1045	0	0	1045

Overview of the destination of the generated amount of waste, biogas is attributed to energy recovery, bio residuals form the process are included in material recycling

Destination	tonnes	share
Waste generated	53902	100%
Energy recovery	29523	55%
Material recycling	19805	37%
Landfill	4504	8%
Vapour	69	0%

Overview of the generated and avoided emissions caused by the pathways of each fraction. Data is given in Kg CO2e./inhabitants.

	Generated emissions		Avoided emissions		
Fraction	Recycling	Incineration	Energy	Material	Net impact
Glass	8	0	0	-9	0
Metal	0	0	0	-11	-11
Plastic	5	39	-10	-14	20
Organic	0	1	-19	0	-18
P&C	34	0	-2	-49	-17
Rest	0	25	-14	0	11

More GB

Amount of each waste type being generated, sorted, material recycled and incinerated (tonnes) according the formula presented in section 4.2.1.

	Generated	Sorted	Recycled	Incinerated
Total	53902	26145	24282	26828
Glass	3236	2883	2883	2912
Metal	948	913	945	920
Plastic	5269	2763	2625	3062
Organic	19525	8519	7040	8519
P&C	13074	11066	10789	11066
Rest	10583	0	0	348
Hazardous	222	0	0	0
Textiles	1045	0	0	0

Overview of the destination of the generated amount of waste, biogas is attributed to energy recovery, bio residuals form the process are included in material recycling

Destination	tonnes	share
Waste generated	53902	100%
Energy recovery	29709	55%
Material recycling	19550	36%
Landfill	4505	8%
Vapour	139	0%

Overview of the generated and avoided emissions caused by the pathways of each fraction. Data is given in Kg CO2e./inhabitants.

	Generated emissions		Avoided emissions		
Fraction	Recycling	Incineration	Energy	Material	Net impact
Glass	12	0	0	-12	0
Metal	0	0	0	-11	-11
Plastic	8	29	-8	-22	8
Organic	0	2	-13	0	-11
P&C	34	0	-2	-49	-17
Rest	0	25	-14	0	11

c. Scenarios for 2030

Perfect collection

Amount of each waste type being generated, sorted, material recycled and incinerated (tonnes) according the formula presented in section 4.2.1.

	Generated	Sorted	Recycled	Incinerated
Total	59989	42995	39043	20956
Glass	3602	3566	3566	36
Metal	1056	1045	1055	11
Plastic	5869	2113	2008	3861
Organic	21710	21710	18218	3492
P&C	14560	14560	14196	364
Rest	11783	0	0	11783
Hazardous	248	0	0	248
Textiles	1161	0	0	1161

Overview of the destination of the generated amount of waste, biogas is attributed to energy recovery, bio residuals form the process are included in material recycling

Destination	tonnes	share
Waste generated	59989	100%
Energy recovery	31145	52%
Material recycling	26798	45%
Landfill	2046	3%
Vapour	0	0%

Overview of the generated and avoided emissions caused by the pathways of each fraction. Data is given in Kg CO2e./inhabitants.

	Generated emissions		Avoided emissions		
Fraction	Recycling	Incineration	Energy	Material	Net impact
Glass	13	0	0	-13	-1
Metal	0	0	0	-12	-11
Plastic	6	38	-10	-15	19
Organic	0	0	-23	0	-22
P&C	40	0	0	-59	-18
Rest	0	25	-14	0	11

Perfect SAR

Amount of each waste type being generated, sorted, material recycled and incinerated (tonnes) according the formula presented in section 4.2.1.

	Generated	Sorted	Recycled	Incinerated
Total	59989	31930	29804	29940
Glass	3602	2314	2314	1288
Metal	1056	1054	1053	34
Plastic	5869	4429	4207	1662
Organic	21710	9573	8033	13461
P&C	14560	14560	14196	364
Rest	11783	0	0	11722
Hazardous	248	0	0	248
Textiles	1161	0	0	1161

Overview of the destination of the generated amount of waste, biogas is attributed to energy recovery, bio residuals form the process are included in material recycling

Destination	tonnes	share
Waste generated	59989	100%
Energy recovery	31145	52%
Material recycling	26798	45%
Landfill	2046	3%
Vapour	0	0%

Overview of the generated and avoided emissions caused by the pathways of each fraction. Data is given in Kg CO2e./inhabitants.

	Generated emissions		Avoided emissions		
Fraction	Recycling	Incineration	Energy	Material	Net impact
Glass	8	0	0	-9	0
Metal	0	0	0	-12	-11
Plastic	12	16	-4	-32	-8
Organic	0	2	-13	0	-11
P&C	40	0	0	-59	-18
Rest	0	25	-14	0	11

More GB

Amount of each waste type being generated, sorted, material recycled and incinerated (tonnes) according the formula presented in section 4.2.1.

	Generated	Sorted	Recycled	Incinerated
Total	59989	32404	29960	29915
Glass	3602	3210	3210	393
Metal	1056	1018	1052	47
Plastic	5869	4104	3898	1970
Organic	21710	11751	9785	11828
P&C	14560	12322	12014	2546
Rest	11783	0	0	11722
Hazardous	248	0	0	248
Textiles	1161	0	0	1161

Overview of the destination of the generated amount of waste, biogas is attributed to energy recovery, bio residuals form the process are included in material recycling

Destination	tonnes	share
Waste generated	59989	100%
Energy recovery	31766	53%
Material recycling	23383	39%
Landfill	4744	8%
Vapour	96	0%

Overview of the generated and avoided emissions caused by the pathways of each fraction. Data is given in Kg CO2e./inhabitants.

	Generated emissions		Avoided emissions		
Fraction	Recycling	Incineration	Energy	Material	Net impact
Glass	12	0	0	-12	0
Metal	0	0	0	-12	-11
Plastic	11	20	-5	-29	-4
Organic	0	2	-15	0	-13
P&C	34	0	-2	-50	-17
Rest	0	25	-14	0	11

d. Comparison

Material layer

Year	Scenario	Plastic recycling	Organic recycling	Material recycling	RoAF recycling
2016	Reference	32%	27%	38%	42%
2022	Reference	32%	27%	38%	42%
	GM col.	32%	27%	40%	44%
	Organic bin	32%	67%	53%	59%
	More GB	50%	36%	45%	50%
2030	Reference	32%	27%	38%	42%
	Perfect col.	34%	84%	65%	72%
	Perfect SAR	72%	37%	50%	54%
	More GB	66%	45%	50%	55%

Energy layer

The values for the scenarios represent the relative changes towards the reference scenario

Year	Scenario	Energy Efficiency	Total out (kwh)	AD (kwh)	Incineration (kwh)	Process (kwh)	Transport (kwh)
2016	Reference	15.0%	4.83E+07	4.93E+06	4.34E+07	2.22E+07	4.95E+06
2022	Reference	15.0%	5.28E+07	5.39E+06	4.74E+07	2.43E+07	5.41E+06
	GM col.	0.04%	0.03%	0.00%	0.03%	-0.6%	2.4%
	Organic bin	10%	9%	153%	-7%	-5%	-3%
	More GB	-6%	-6%	36%	-11%	2%	5%
2030	Reference	15.0%	5.88E+07	5.98E+06	5.28E+07	2.70E+07	6.04E+06
	Perfect col.	6.5%	6.9%	216.6%	-16.9%	4.5%	4.5%
	Perfect SAR	-21.9%	-21.2%	39.6%	-28.1%	11.0%	11.2%
	More GB	-11.7%	-11.4%	70.1%	-20.6%	3.8%	8.2%

Detailed overview of the transport energy requirement.

Year	Scenario	Collection Energy	RW (kwh)	P&C (kwh)	G&M (kwh)	GB (kwh)	Downstream Energy (kwh)
2016	Reference	1.98E+06	1.16E+06	4.09E+05	1.23E+05	2.87E+05	2.97E+06
2022	Reference	2.16E+06	1.27E+06	4.47E+05	1.35E+05	3.14E+05	3.25E+06
	GM col.	2.1%	-3.3%	0.0%	63.0%	0.9%	2.6%
	Organic bin	5%	-22%	0%	0%	119%	-8%
	More GB	2%	-14%	0%	63%	40%	8%
2030	Reference	2.42E+06	1.42E+06	5.00E+05	1.50E+05	3.50E+05	3.62E+06
	Perfect col.	13.3%	-48.6%	29.8%	84.1%	210.4%	-1.4%
	Perfect SAR	0.0%	0.0%	0.0%	0.0%	0.0%	18.7%
	More GB	1.5%	-22.7%	0.0%	63.4%	75.4%	12.6%

Emission layer

The values for the scenarios represent the relative changes towards the reference scenario

Process emissions

Year	Scenario	Process (kg CO2e.)	Sorting (kg CO2e.)	Recycling (kg CO2e.)	Incineration (kg CO2e.)
2016	Reference	2.29E+07	1.33E+05	9.38E+06	1.34E+07
2022	Reference	2.51E+07	1.45E+05	1.02E+07	1.47E+07
	GM col.	2.6%	-2.5%	6.7%	-0.1%
	Organic bin	-1.0%	-35%	0.5%	-2%
	More GB	-4%	-3%	13%	-15%
2030	Reference	2.79E+07	1.61E+05	1.14E+07	1.64E+07
	Perfect col.	6.8%	-53.1%	23.6%	-4.3%
	Perfect SAR	-9.1%	-0.5%	26.5%	-34.0%
	More GB	-9.8%	-2.7%	18.6%	-29.7%

Transport emissions

Year	Scenario	Transport (kg CO2e.)	Collection (kg CO2e.)	Downstream (kg CO2e.)
2016	Reference	9.75E+05	1.80E+05	7.95E+05
2022	Reference	1.07E+06	1.80E+05	8.87E+05
	GM col.	0.1%	-11.9%	2.6%
	Organic bin	-6%	4%	-8%
	More GB	4%	-13.8%	8%
2030	Reference	1.19E+06	2.06E+05	9.89E+05
	Perfect col.	-3.1%	-11.2%	-1.4%
	Perfect SAR	15.5%	0.0%	18.7%
	More GB	8.1%	-13.3%	12.6%

Avoided emissions

Year	Scenario	Total Generated (kg CO2e.)	Total avoided (kg CO2e.)	Energy recovery (kg CO2e.)	Material recycling (kg CO2e.)	Climate impact (kg CO2e.)
2016	Reference	2.4E+07	-2.4E+07	-7.2E+06	-1.6E+07	3.95E+05
2022	Reference	2.6E+07	-2.6E+07	-7.9E+06	-1.8E+07	4.35E+05
	GM col.	2.5%	2.9%	0.0%	4.1%	3.65E+05
	Organic bin	-1.2%	7%	23%	0%	-1.67E+06
	More GB	-3%	9%	-1.9%	13%	-2.69E+06
2030	Reference	2.9E+07	-2.9E+07	-8.7E+06	-2.0E+07	4.97E+05
	Perfect col.	6.4%	20.3%	26.8%	17.5%	-3.45E+06
	Perfect SAR	-8.1%	17.2%	-15.4%	31.5%	-6.78E+06
	More GB	-9.0%	14.2%	-3.7%	22.1%	-6.21E+06