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

Case study Trondheim

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Master in Industrial Ecology
Submission date: July 2017
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Preface

With this report I conclude my master's degree in Industrial Ecology at the Norwegian University of Science and Technology, June 2017.

During the model development more time than expected was spent on solving issues related to the coding of the model. Originally, the project comprised the effects of enhancing material recycling on greenhouse gas emissions. In agreement with supervisor, this particular work has been left out of the thesis.

The same model was the foundation for the thesis work of my co-students Nora Schjoldager and Pieter Callewaert, and I would like to thank them for exchange of ideas and support. I would also like to thank my supervisor Professor Helge Brattebø at NTNU and co-supervisor Knut Jørgen Bakkejord from Trondheim municipality for guidance and assistance throughout this work.

Summary

The management of the natural output of consumption, waste, has to become more sustainable. Ideally this would mean that it simply ceased to exist, but as unrealistic that may be, the current discourse in waste legislation and management is on increasing the material recycling rate. This is a part of the circular economy. Analysing waste management systems is crucial to know what effect different measures might have on the actual recycling rate. In turn, these measures might impact the energy consumption related to all this waste management.

To comply with future possible new policy targets related to the circular economy and decrease its environmental impacts, the municipality in Trondheim intends to implement several measures to improve its waste management. A dual-layer material flow analysis model was developed and customized, and scenarios designed to test the effects of planned measures in Trondheim's waste management.

The scenarios with an improved central sorting facility and improved household sorting efficiency gained the highest material recycling rates, while having a negative impact on the system energy efficiency as a result of more energy consumption in treatment and less energy output from the local incineration plant. The energy efficiency was highest in the scenario where most waste was sent for incineration with co-generating heat. The fraction with the highest impact on material efficiency compared to the reference scenario was the organic waste fraction, due to it not being collected in the reference scenario in the first place, and due to the large share it constitutes of the total waste generated.

With the material recycling rate as defined in the model, the municipal material recycling target of 50% were met for both exploratory improvement scenarios, whereas only the perfect household scenario reached the target in 2020. All scenarios failed to reach the target of 70% material recycling of household solid waste in 2030. Yet there is hope, as the real material recycling rate is likely to be higher due to waste categories and sources not included in this mode. To reach probable future targets as legislated by the EU, this study recommends that the municipality go forth with its current plans, but additional effort in improving household sorting is required to have a realistic chance at the increased future targets set by the EU.

Sammendrag

Måten vi håndterer forbrukets naturlige sluttprodukt på, nemlig avfallet, er nødt til å bli mer bærekraftig. Helst ville dette betydd at det simpelthen sluttet å eksistere, men siden dette ikke er helt realistisk er det nåværende temaet innenfor avfallsdebatten å øke materialgjenvinningsgraden. Dette er en del av kretsløpsøkonomien. Analyse av systemer for avfallshåndtering er vesentlig for å kjenne hvilke påvirkninger ulike tiltak har på materialgjenvinningsgraden. På den andre siden kan disse tiltakene påvirke energiforbruket forbundet med avfallshåndteringen.

For å tilfredsstille mulige, fremtidige avfallsmål som mer og mer følger kretsløpsøkonomi-tankgegang og samtidig redusere sin påvirkning på miljøet har Trondheim kommune planer om flere tiltak for å forbedre avfallshåndteringen. En tolagsmodell basert på

materialstrømanalyse-metodikk ble utviklet og tilpasset, og den ble kvanfisiert for avfallsstrømmene fra husholdningene i Trondheim kommune, med det mål å undersøke virkningen av disse planlagte tiltakene på systemet.

Scenariene med et forbedret sentralsorteringsanlegget og forbedret kildesortering hos innbyggerne oppnådde den høyeste materialgjenvinningsgraden, samtidig som de trakk systemets energieffektivitet ned som en følge av et høyere energiforbruk i nedstrøms behandling og mindre energiproduksjon ved det lokale forbrenningsanlegget. Energieffektiviteten var høyest i scenariet med størst mengde avfall sent til dette forbrenningsanlegget som også produserer varme. Avfallsfraksjonen med høyest påvirkning på materialgjenvinningsgraden sammenlignet med referansescenariet var matavfallsfraksjonen, ettersom matavfall ikke var en den av innsamlingen i referansescenariet og fordi matavfall utgjør en såpass stor andel av samlet avfallsgenerering.

Med materialgjenvinningsgrad slik som den er definert i denne oppgaven klarte begge de utforskende og forbedrede-tiltak-scenariene å nå det kommunale avfallsmålet på 50%, mens kun det perfekte husholdningsscenariet nådde EUs mål om 60% materialgjenvinning i 2020. Ingen scenarier klarte å nå det nyeste målet om 70% materialgjenvinningsgrad av husholdningsavfall i 2030. Likevel er det håp, ettersom den sanne materialgjenvinningsgraden mest sannsynlig er høyere som en konsekvens av relevante avfallsmengder med høy gjenvinnningsgrad som ikke er med i denne modellen. Uansett er anbefalingen at kommunen holder frem med sine nåværende planer, men for å ha en realistisk sjanse til å nå de høye målene satt av EU trengs det mer innsats på å forbedre kildesortering i hjemmene.

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List of definitions and acronyms

aggregated category Almost the same as *waste fraction*

CSF central sorting facility

EU the European Union

G&M glass and metals, a waste category

LCA Life cycle assessment

MRF material recovery facility

MFA Material flow analysis

MRR material recycling rate

MSW Municipal solid waste

P&C paper and cardboard, a waste category

recovery treatment processes which leads to waste serving a useful purpose, recycled or other

recycling the processing of the waste materials into products, materials or substances

SWM solid waste management

waste fraction/subfraction a defined group of similar waste materials, such as hazardous waste or plastics

the actual material content of a waste fraction, in pure (organic) or aggregated (paper, cardboard) categories

waste category / type a group of waste fractions which is collected separately in a waste management system, such as paper and cardboard

one of several waste categories collected by the waste management company, typically plastic, organic or residual waste

TC transfer coefficient

TRV Trondheim Renholdsverk (Trondheim sanitation company), the company in charge of waste management in Trondheim

1 Introduction

1.1 Background

It is becoming increasingly more apparent how a focus on sustainability has to be reflected in each and every part of society as climate change and resource depletion create conflicts and harsh conditions for people all over the world. In 2015 the United Nations adopted the sustainable development goals as global planning objectives for 2030, recognizing that sustainability has to be at the forefront when tackling the issues of today and in the future. The 17 goals reflect the three spheres of the notion of sustainable development: the environmental, the economic and the social (Johannesen 2017) sphere.

Waste management consumes water, energy and requires land, and it produces direct emissions of greenhouse gases, from transportation work, incineration plants and landfills; in summary throughout the whole of its life cycle (Det europeiske miljøbyrået 2016). The challenges in sustainable development are the same as in waste management (Pires, Martinho, and Chang 2011). Climate change, which can be mitigated by reducing GHG emissions in waste treatment; energy crisis, which can be helped by energy recovery from waste treatment and increase the energy efficiency of management systems; and resource depletion, which is helped by reducing waste generation and recycling the materials in waste.

The definition of waste is an unwanted product, and unwanted products means misplaced resources. This is changing in the EU, with their now soon nine year old Waste Framework Directive and their 2015 Circular Economy Package. This legislation is the EU's intention to improve the sustainability and circularity in their waste and resource industries, at the same times increasing competitiveness and job creation. Increasingly we see that a requirement for sustainability is the transition from a linear to a circular economy, where waste production is minimized and resources conserved inside the circular loop as much as possible, increasing the resource efficiency. The inspiration in this respect is nature, where no resources go to waste.

1.2 Motivation

The municipality of Trondheim experiences the same thing as most urban areas globally; a growth and congestion which creates a waste problem and burdens the infrastructure. In accordance with national and EU targets, the municipality of Trondheim intends to improve its environmental footprint and a part of that is the material recycling of the waste it collects and measures to create a more circular economy. Like ecosystems, an economy is a dissipative system which needs a source of energy to move material flows around in vegetation and animals, but the circular economy is even more dissipative, as the complexity rises with the number of recycling and conserving processes. A consequence of this is that the circular economy could depend on a higher throughput of energy. Therefore, waste system analysis to regard the potential tradeoffs when increasing one attribute of the system - the material recycling rate - is important in planning for sustainability.

The main objective in this project is to investigate sustainability performance for the waste management system for waste generated in the municipality of Trondheim. The scenarios will apply already planned measures in the years ahead for improving the waste management in Trondheim. The method used will be a dual-layer material flow analysis model to analyze these flows and identify critical spaces for improvement. Continuing the project work, this model includes all the waste categories currently collected by the waste management in Trondheim and adds an energy layer to look at the effects of increasing the material efficiency of the system. With this model I hope to answer the following questions:

- What is the system performance of the current household solid waste management in Trondheim and modelled scenarios with regards to material recovery and energy use?
- What are the critical system variables and influencing factors?
- What are the effect of new measures on system performance?
- How can targets be met, and what implications will this have for current and future policy?

2 Literature review

2.1 Waste engineering and management

Waste engineering seeks to solve the issues of waste generation. It started out with simply getting it out of the way by landfilling or burning, these days we are more focused on reducing impacts along its whole life cycle. Waste management can be defined into the following stages: waste generation, its collection and its treatment and disposal through technologies such as incineration, landfilling and material recycling. Each step takes place at different locations and have different impacts on the environment and resource use.

Current waste management is built on the fundamental principle of the waste hierarchy. The waste hierarchy illustrates the knowledge each downstream stage in waste management has on the environment and shows how important each stage is to have the largest effect on preventing environmental impacts and resource use. Preventing waste from arising in the first place will of course prevent any waste management to take place. Then we go about re-purposing, recycling and treating the remainder to the best of our knowledge and capacity.

The cradle of the problem lies in the generation of waste. To understand waste, proper characterization is needed. Waste can be characterized by origin, material (fraction), weight, or related to another unit, such as tons per year or per capita. Most waste is household waste, followed by industrial and construction and demolition waste.

2.1.1 Collection and transportation

Collection can be defined as any actions occurring from the moment a resident leaves waste in a public receptacle until it is either stored or sent to treatment elsewhere. Waste is separated into different categories/bins based on local policy in a particular area, and in some places, is designated different colored bags depending its content. Receptacles are either emptied by machine, by hand or brought in with varying sizes of trucks, depending on the type and size of receptacles they will serve. Receptacles comes as two-wheeled bins, ranging from small ones 50 m^3 to larger four-wheeled bins holding 400 m^3. Larger receptacles such as bottom-holed containers and underground containers are emptied into a special kind of truck with a lift. Underground containers require some planning due to space requirements underground interfering with sewage and other cables, but as a solution it improves the local environment with less mess and space occupied on a surface level. High quantities - clients might see fit to order metal containers to be transported back and forth as it fills up.

In the last ten years further developments in the high-density living areas have been made into the research and implementation of vacuum systems. They have emerged as an efficient way to serve a large area, with sparse space needed on top, and without interfering in the surface planning. Areas might be planned without need for large vehicle access, as the disposal intakes and collection of waste are separated by the vacuum tubing. Problems with vacuum system is they take are planning, you have to plan ahead the number of intakes depending of your waste system, you need to build separate infrastructure, and the drop might adversely impact any bag-based sorting system as gravity wrecks havoc on dropped bags.

2.2 Municipal solid waste system assessment

Applying system engineering thinking, a MSW management system can be considered a system of sub-systems, where each treatment process such as collection, incineration and landfilling are separate components which relate through the exchange of processed waste streams (Pires, Martinho, and Chang 2011). The last decades, MSW management has been the subject of a variety of assessment methods and techniques of systems analysis, such as cost-benefit-analysis, environmental impact assessment, life cycle costing and life cycle assessment (Allesch and Brunner 2017). Considering that *local communities in the EU regard MSW management decision making as important for sustainable development* (Pires, Martinho, and Chang 2011), continued improvement of both systems and assessment methods is important to support.

2.2.1 Assessment categorization

Pires et al (2011) performed a comparative analysis of MSW systems analysis/performed a review of various waste assessment methods in European countries and found that *the most common practices for waste management in European countries are those using various systems assessment tools rather than system engineering models.* Most analyses was applied to MSW as a whole. The most popular tool for system assessment was LCI/LCA, and the second most popular tool was the ORWARE model, mainly developed in Sweden, combining MFA and LCA to model and evaluate MSW and BMW systems. The ORWARE model was specifically useful to research the link between solid waste management and energy-recovery, not surprisingly, considering the large number of incineration plants in EU as a whole.

2.2.2 MFA and LCA in SWM assessment

As the selected modelling methodology in this thesis is grounded in industrial, I found it of interest to include a brief review on the application of MFA and LCA (two of the most common industrial ecology methods) in solid waste management assessment.

2.2.2.1 MFA

Material flow analysis are increasingly finding use for waste management, with an ever increasing number of articles published the last five years. Material flow analysis is often carried out in solid waste management assessment to help decision making and makes *for a consistent and copmlete data set* to be built upon with additional assessment methods, such as LCA (Allesch and Brunner 2017). Allesch and Brunner (2017) state that results of their MFA results reveal benefits of a mass balance approach in waste management due to redundancy, data consistency, and transparency for optimization, design and decision making.

2.2.2.2 LCA

Both material and energy use in waste systems have been explored by a number life-cycle-assessment since they first started taking place in the late 90s. Most analyses regarding waste and energy focus on single processes or facilities or the thermodynamics of a single facility - there is a lack of assessment for system-wide, holistic integrated system assessment. Life-cycle assessments do more focus on a product than on a whole system.

2.2.3 Indicators

Performance indicators are used to compare different scenarios, and where standardized and widely accepted they also allow cross-study comparisons. A summary of performance indicators by Rigamonti, Sterpi, and Grosso (2016) states how measuring performance of waste management systems is not new. A whole series of system indicators have been proposed, assessing energy conservation of the system, actual limits to recycling using the services provided, a system's capacity in closing its loops, the resources spared from recovering resources in waste streams (Rigamonti, Sterpi, and Grosso 2016).

Rigamonti, Sterpi, and Grosso (2016) themselves developed a composite indicator to assess the environmental and economic sustainability of MSW, intended to be as simple as to be calculated by waste management professionals themselves and not only LCA practitioners. The environmental sustainability levels are defined by quantifying two indicators: Material Recovery Indicator MRI and Energy Recovery Indicator (ERI), based on their experience from previous LCAs that energy and material recovery levels are what decides the environmental performance of an MSW system.

Another study, focused on material recovery only, for their MFA-analysis of waste collection flows in a group of municipalities Zaccariello, Cremiato, and Mastellone (2015) designed a set of indicators to measure the efficiency of the waste collection, depending of selection of bin set (separate or mixed bin collection of specific fractions). Their defined "actual interception efficiency" measures the actual content of a defined material in a category over the generated amount of that particular material. Such an efficiency - disregarding contamination - will be important to see the losses owing to both household separation and waste management collection processes. Further indicators based on the amounts of recycled amounts and actual recycled amounts of material to the amounts of material collected - indicating loss further downstream in two different solutions.

2.3 The circular economy

In the EU, waste generation is around 6 tons per person every year (EEA 2016). The growth in waste generation points to a larger issue: the growth in consumption of resources. The world's current consumption of natural resources is not sustainable in the long run and has not been since the seventies (Wackernagel et al. 2002). Also, CO2-emissions are closely related to the material consumption and production (Hertwich and Peters 2009). To reach sustainability and mitigate climate change, it is therefore paramount that we lower our of virgin natural resource material consumption. The challenge is how to recover or prevent these six tons of waste. It is necessary to recover the resources in the waste, preferably suffer as little loss as possible of the resources after harvested from the natural occurrence. This is also the goal of the so-called circular economy, keeping materials in the loop in the form of circular waste management is something we put a lot of hope in to reach this goal.

With regards to material recovery, the EU Waste Framework Directive sets the following target for 2020: that minimum 50% by weight of materials in waste such as paper, metal, plastic and glass from household and household-like sources be recycled or see re-use (*Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives* 2008).

The most important development, however, recently, is the adoption of the 2015 Circular Economy Package, revising and amending the waste framework directive to "*to stimulate Europe's transition towards a circular economy which will boost global competitiveness, foster sustainable economic growth and generate new jobs*" (Navigation path and European Commission 2016). The package focuses on resource efficiency and considers the whole life-cycle of products, being a part of a action plan for the circular economy and green growth through closing the loop (Navigation path and European Commission 2016). New goals for material recovery were proposed in the amendment, that the targets in 2020 for waste types such be extended to 60% recovery in 2025 and 65% recovery in 2030.[1 2].

2.3.1 Assessment for the municipality of Trondheim

Finally, the municipality has had several reports and analyses performed during its strategic long-term planning of waste treatment. Of particular focus have been investigating potential consequences from diverting organic waste from incineration to alternative treatment. One of them is an analysis performed by NORSAS in 2010. Norsas (2010) looked at environmental consequences of including organic waste in household waste management in Trondheim. A simple life cycle analysis was performed. Emissions-wise the conclusion was that incineration is better than separation of organic waste. This was based on the assumptions that, and with another system boundaries, the results would end up quite different.

[1] The targets in this section are not the latest targets as by July 2017

[2] (*Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL Amending Directive 2008/98/EC on Waste* 2016)

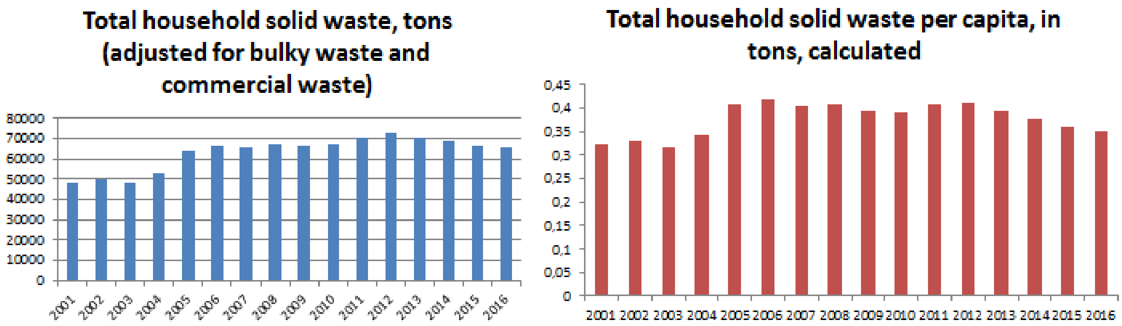

Figure 1: Total municipal waste and total municipal waste per capita for Trondheim, 2016. Adjusted for industrial waste.

3 Case study

The case study brings an overview over the most central parts of the municipal solid waste management system of Trondheim.

3.1 Waste management in Trondheim

Housing the third largest city in Norway, the municipality of Trondheim has 187 353 inhabitants as of January 2016 (Statistisk sentralbyrå, n.d.). The total collected household solid waste of the same year, seeing a gradual decrease the last four years (Statistisk sentralbyrå 2017). The average household waste collected per capita in Trondheim was 350 kg in 2016 (Statistisk sentralbyrå 2017), but due to a steady population growth it has decreased more than the total quantities, with 3-4% in the last four years, after a period of stagnation, see figure 1. A key cause of reduction is reduced generation of paper and cardboard waste (Trondheim kommune, kommunalteknikk, n.d.). Average waste collected per capita in Norway was 439 kg in 2015 (Statistisk sentralbyrå 2016a), and we see that Trondheim has a way smaller waste generation.

In Norway legislation grant municipalities both the right and the obligation/responsibility to collect and manage household solid waste (*Lov om vern mot forurensninger og om avfall (forurensningsloven) - Lovdata* 2016, sec. 30). The municipality does not have to perform the management itself, it can hire contractors in the competitive market. In any case, the task at hand has to be a call for tenders. For the purpose of collecting household waste, the municipality established the company Trondheim renholdsverk (TRV) in 1918 (Trondheim renholdsverk 2016). Today TRV is part of TRV-gruppen (the TRV-group), a stock-based limited company, and TRV continues to operate the day-to-day collection of municipal household waste, including waste from public institutions, and the public waste collection center Heggstadmoen gjenvinningstasjon. Its operations are financed by sanitation fees from residents in the municipality. TRV's premises at Heggstadmoen is also the location for storage of residual waste for incineration, for glass and metals before it is trucked further. Next to TRV Retura, TRV's for-profit sister company, is located, and its sorting facility which handles the sorting of plastics and paper.

3.1.1 Current chains of custody of solid waste collected by the municipality

Municipal solid waste in Trondheim is collected through two receptacle systems: curbside collection and public collection points. The curbside collection is both scheduled and permanent, and includes the three waste categories plastic, residual waste and paper/cardboard. These three are collected either from wheeled bins, moloks or underground containers of varying sizes or increasingly in central or mobile vacuum systems. In general, the higher the density of dwellings, the larger the containers provided (Stabsenhet for byutvikling 2010).

Residual waste, including household organic waste which is not source-segregated, is collected every week - every second week depending on location (Eirik Almås Rønning, personal communication). Then, depending on demand for energy and waste, it is either taken to a storage location nearby at Heggstadmoen, or directly transported to the incineration plant Heimdal varmesentral at Tiller, owned by the district heating company Statkraft varme (Statkraft Varme 2016), located less than 10 km away in neighboring municipality Heimdal.

The bottom ash produced to through sorting by Retura at Heggstadmoen, where aluminum, steel and slag iron are sorted out and sent for recycling, according to data provided by Retura. Remaining bottom ash is shipped to final deposition at a landfill (Langøya) on an island ca. 50 km south of Oslo ("Fakta om Langøya" 2017). At Langøya there is a facility for treatment of flue gas, bottom ash and other inorganic waste. Chemical staiblization happens by the addition of ferrous gypsum.

Plastic waste is collected with a lower frequency than residual waste, due to its cleanliness and lower weight (7 times - 26 times in city center, according to data from Eirik Almås Rønning, by personal communication). After collection plastic is be sorted and baled at Heggstadmoen. It is stored until a larger loads are ready for transport to Germany, on trucks or train, organized by Grønt punkt Norge (recycler of used packaging) (Morten Hjorth-Johan, by personal communication). The plastic is then sent to large sorting and recycling facilities in Northern Germany. It is sorted into 5 - 7 types of plastic, where some are chemically recovered at location while others are shipped further for recycling at other plants ("Plastemballasje fra husholdninger" 2017).

Paper and cardboard, collected 13, 52 or 104 a year depending on location, are also put through the sorting facility at Heggstadmoen, and sorted into cardboard, paper and cardboard packaging: paper is sent to the paper mill Norske skog at Skogn, cardboard to Ranheim and liquid packaging board to Sweden. From public collection points glass and metal packaging is collected by the TRV on call. The municipality provides the containers. The waste is weighted at Heggstadmoen upon entrance and it is stored there until picked up for transport/Glass and metal packaging are taken to storage at TRV/Heggstadmoen. The next step is to be trucked (by tender - in 2016 - Børstads transport) to Syklus on Onsøy outside of Fredrikstad for sorting and recycling. From there aluminium is sent to Metallco, steel to Celsa stål in Mo i Rana, glass to glass factories in continental Europe or one of Syklus' own factories of Glasopor foam glass in Fredrikstad or Skjåk (Solberg 2017). Any remainder material goes to final deposition.

Finally, TRV collects some waste categories which will not be a part of this model and study. Small amounts of hazardous waste is collected curbside on a low-frequency

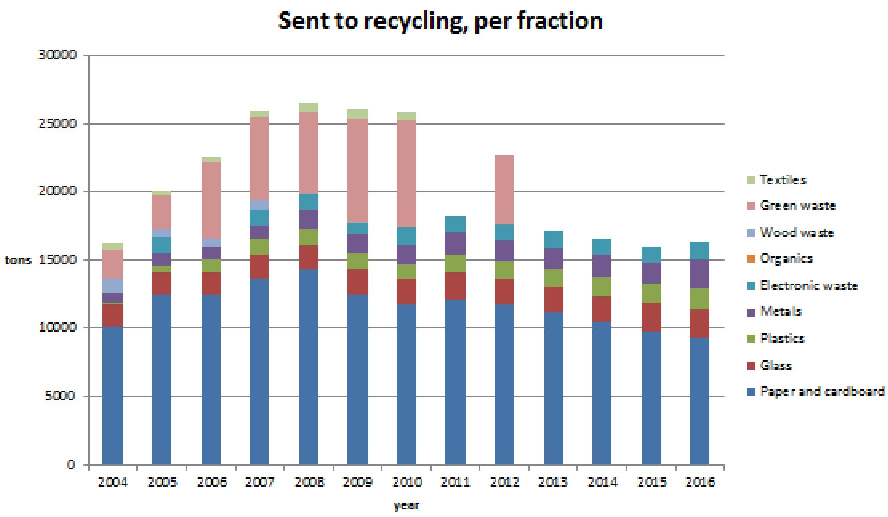

Figure 2: Sent for material recycling over total household waste. Based on KOSTRA-data

schedule. There are also additional categories for waste delivered to the local MERF at Heggstadmoen, such as garden waste and actual metals parts (bulky waste). TRV also collects municipal institutional solid waste, at around 10% of total waste generated. Because of this, some of the data used in the model for assumptions on collection and transportation will be a little bit off.

3.2 Policy, issues and planned measures

3.2.1 Material recovery

One of the main targets of in the municipality's waste planning is to increase the material recovery rate. Figure /ref{fig_trv-matrec} shows the development in the material recovery rate as reported by the municipality. Green waste sent to composting is considered material recovery. We see that it has been declining since 2011, except for the addition of garden waste numbers. The outliers in 2011 is due to a missing data or another practice in reporting park and garden waste. Removing green, textile and electronic waste, what's left is what the municipality collects curbside, which consists mainly of packaging of different kinds as well as residual waste. With this definition, we see then that the material recovery rate is only around 22%.

Of course, organic waste, which is not segregated, even, is helping dragging down the average by its absence. Figure illustrates how residual and paper and cardboard makes up the major part of waste collected. A weighed averaged of results of a sampling analysis performed by Mepex Syversen and Bjørnerud (2016a) showed that the residual waste fraction in Trondheim consists of around 45 % organic waste. Recovering only half of this would be likely to raise the total recycling rate above 40%. In 2007 the municipality had a 85% recovery in total, where around 40% was material recovery and the remaining from energy recovery by incineration (Stabsenhet for byutvikling 2010). Meeting the goal is then a function of what material recovery rate and the energy efficiency of the incineration plant, each trading off the other.

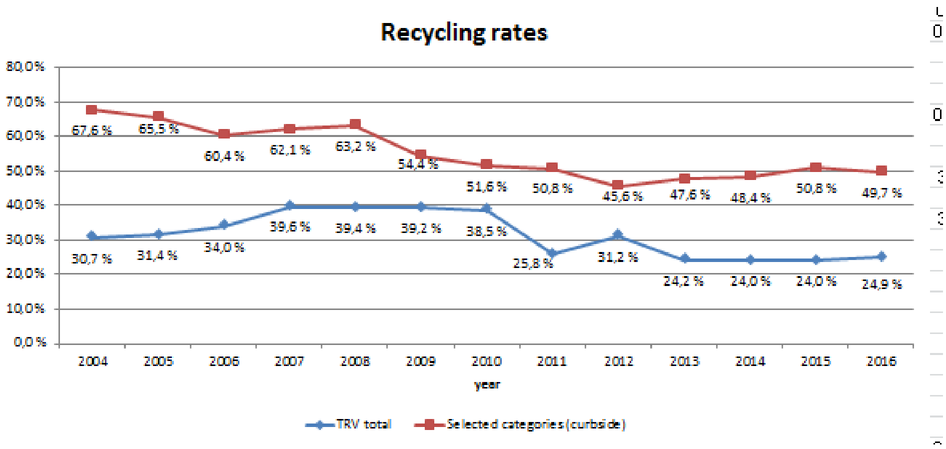

Figure 3: Sent for material recycling, overall and curbside only. Based on KOSTRA-data

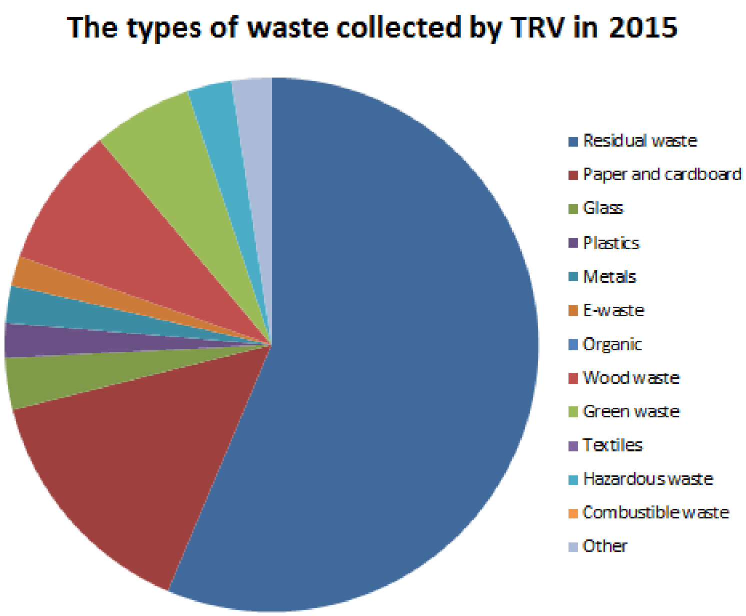

Figure 4: Waste category disitribution for TRV, 2015. Based on KOSTRA-data.

3.2.2 Policy targets

Waste management in the municipality is governed by two documents, a waste management plan (for the period 2007 - 2016) which sets out status, possible measures, strategy and the main targets (Miljøenheten, Trondheim Byteknikk, and Rambøll Norge AS 2007) and an action plan for the actual implementation. Of the objectives the municipality lists in its waste management strategy, the most relevant for this project is the one regarding resource utilization and emissions.

The first target concerns waste reduction, where the municipality is to contribute to stop the growth in household solid waste. Further targets for resource utilization are that 90% of household solid waste be recovered, and a minimum of 40% be materially recycled. Long term material recycling rate should be increased further by source segregating organic waste. Emissions has a target, too; any emissions from the collection and treatment of household solid waste should be kept as low as possible (Miljøenheten, Trondheim Byteknikk, and Rambøll Norge AS 2007).

The municipality anticipates that the EU directive on waste will bring on the following for Trondheim waste management (Stabsenhet for byutvikling 2010):

- the need for measures to increase material recycling rates to over 50%
- future regulations on the treatment of household organic waste, for instance, ban on incineration or required separation
- secondary material and other products of recycling will increase in competitiveness and use - and the possibility that the emissions balance could be improved through procurement of such products

As of spring 2017 the EU has updated its target of material recovery in 2030 to 70%. This concerns household solid waste and waste of similar composition.

3.2.2.1 Issues and measures

Some of these measures will be explored in the scenario development.

For Trondheim, improving the material recycling rate would mean that:

- households have to improve their sorting -> communication and education. The action plan states that if households did sort their waste properly, the material recovery (as currently calculated) would be more than 60% (Stabsenhet for byutvikling 2010).
- send less material for incineration -> separate out organics
- make sure wrongly sorted resources are still recovered -> central sorting

As of June 2017, a new waste plan for 2018 - 2020 is in the works, following up on new targets from the EU and the Norwegian government. A preliminary plan proposal states that in order to hit the 2020 EU target of 50% material recovery sorting out organic waste is of essence, but increased recovery of other kinds of material is also necessary (Trondheim kommune, kommunalteknikk, n.d.).

The municipality has been researching the environmental impacts and benefits of utilization of organic waste for biofuel production. The idea is to lead this flow to produce carbon-neutral fuel, utilize the nutrients in the organic waste and also having a cleaner operation/collection overall. The collected organic waste would be directed to Ecopro's biogas plant at Verdal, which is currently processing bio waste by way of anaerobic fermentation (Fløan 2016).

As for plastics, constituting a very small percentage of total quantity, its usefulness in separation have been questioned as its large volumes makes for expensive collection. Still plastics are a valuable and with a central sorting plant it would be cheaper to extract more of the generated fraction than at present, increasing its value further than today (Knut Jørgen Bakkejord, by personal communication). For central sorting to be feasible, though, more organic waste has to be separated out from the residual waste, as it soils and degrades all other potentially recoverable materials. Current plans are to complete the construction of and do a test run at a local central sorting facility by 2020 (Bakkejord, n.d.). The RoAF central sorting facility at Skedsmo north of Oslo will be the model, probably with some adjustments suggested based on experience from the operation of the RoAF (waste processing in Romerike) facility (Knut Jørgen Bakkejord, by personal communication).

Collection system

Looking forward, one wants to continue separating plastics, paper/cardboard and residual waste, and add organic waste, totaling four waste categories (Stabsenhet for byutvikling 2010). Due to space issues, Trondheim can't just put up four different receptacles all over town. Like Norway as a whole ("Framskrivning av ordinært avfall 2011 til 2020" 2012) Trondheim has not managed to separate growth in economic activity and waste generation. Additionally, from population projections the population in Trondheim is posed to grow by 6% by 2020 compared to 2015 (Statistisk sentralbyrå 2016b), and already there are space issues in older, denser parts of the city, related to the curbside collection of waste. The issues relate both to lack of space for locating additional receptacles and overridden receptacle capacity. In the future more waste and collection of organic waste will require more frequent collection of especially small bins, as 40% of waste volume in 2020 will still be put into small bins (Stabsenhet for byutvikling 2010).

As set targets in their action plan, the municipality has started to increase the use of vaccuum systems and underground receptacles for new building projects, and to renovate areas to do the same (Stabsenhet for byutvikling 2010). Such collection solutions will both increase the service level for households and lower the transportation impacts, due higher capacity receptacles and need for less transport, but they need to be planned for.

Currently, the most likely proposal for receptacle set is a two-receptacle system and bags requiring bag color identification at a central sorting facility post-collection further sorting post collection (Bakkejord, n.d.). Paper and cardboard would continue as a separate receptacle, while the remaining three categories would be collected in a common receptacle each in separate colors, or potentially with plastics free floating. Reducing the amount of receptacles from two to three could has the potential to increase both service level and material recovery rates because of easier recycling when everything is put into the same bin. The hard work happens at kitchen level.

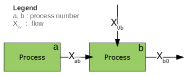

Figure 5: Describing processes

4 Methods

This chapter describes the methods I have been using for this work. The collection of data was done either from consulting literature and reports, through communication with employees at the respective companies by mail or phone, and a handful of meetings in person facilitated by my previous co-supervisor. The model was developed further from the model in the project work last fall, extending it with two more waste categories and an energy layer. Further iterative improvement of model was based on presenting preliminary results to my supervisor and previous supervisor, especially to question and correct unlikely assumptions.

4.1 Material flow analysis

Material flow analysis (MFA), as defined by Brunner and Rechberger in their MFA handbook (2004), is a method of systematically assessing stocks and flows of materials or substances within a system defined in space and time. A system in MFA is defined as a group of elements (processes and flows), their interactions and the boundaries both between these elements themselves and elements on the outside of the system (Brunner and Rechberger 2004). The actual material in an MFA is goods, made up by several substances, and defined as economic entities (Brunner and Rechberger 2004). A process is the "transformation, transport or storage of materials". A process itself might be broken up into several sub-processes, or it might be what forms the entire system. A flow is simply an input to or an output from a process, typically valued in t/a or kg/a (a mass value over a time value, a signifies years). A flux is a subsection of a flow to make it easier to compare across processes and systems, for instance, the waste generation in a municipality per capita (Brunner and Rechberger 2004).

Any time there is more input to a process than outputs it contributes to buildup of material mass, so-called stocks. In waste management a typical stock would be everything which is storage related and stored across the unit of time, in particular any processes related to final disposition at landfill. In this model stocks are not used.

MFA links processes together by their inputs and outputs and estimates their size by applying the principle of mass balance. What makes it all possible is the law of conservation of matter, which states that matter never disappear but is simply transformed. All inputs to a process must - in some form or other - also come out. This is illustrated in equation 1, where x is a flow and m means mass.

$$\sum_x m_{input} = \sum_x m_{input} + m_{storage} \tag{1}$$

In figure 5 a process and its nomenclature as defined in MFA is shown.

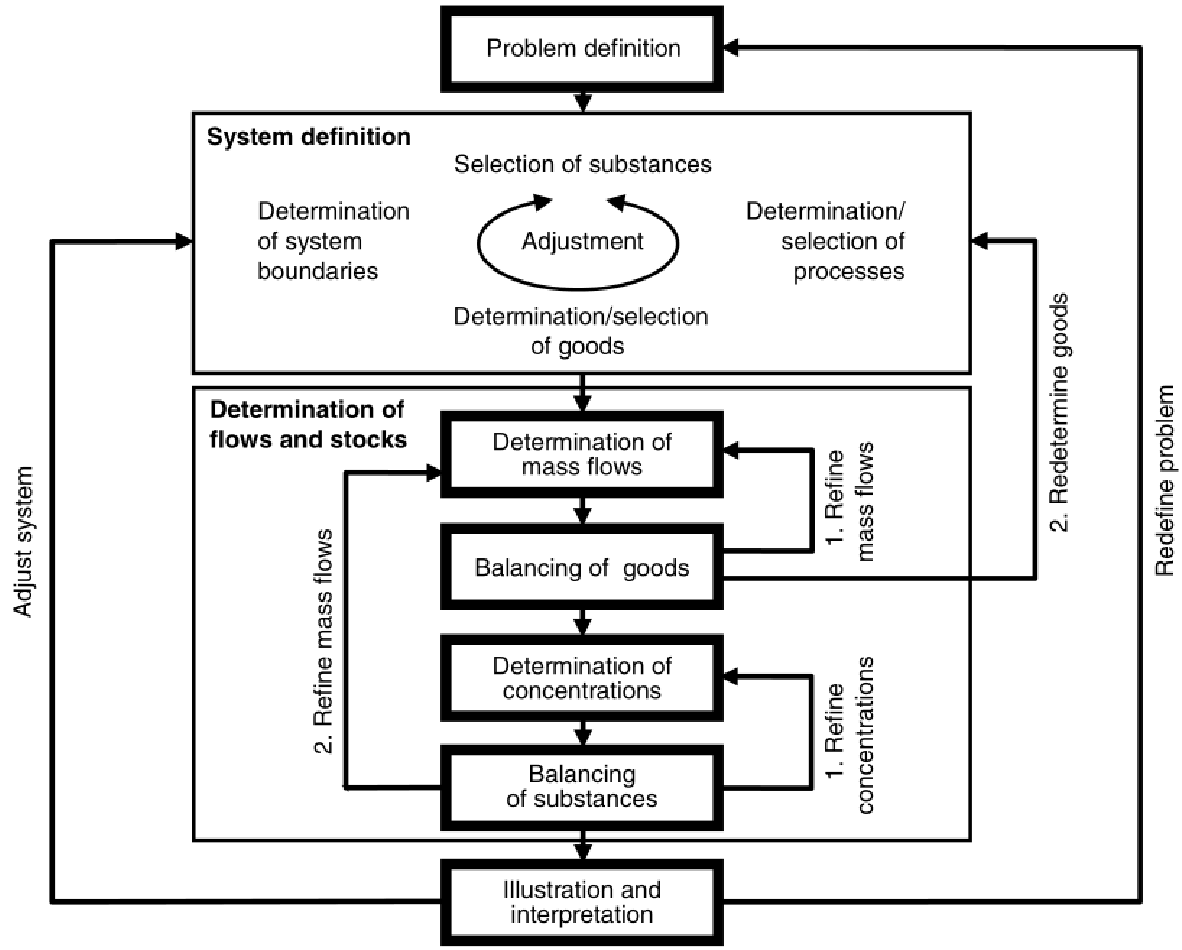

Figure 6: Procedures for MFA. Taken from the MFA handbook by Brunner and Rechberger.

Flows are calculated from the application of transfer coefficients on known values. Also knowns as TCs, transfer coefficients are particular to a process, technology-dependent and they describe how goods are partioned in a process (Brunner and Rechberger 2004). They detail the transformation of useful matter into wastes and the increase in entropy with each step down the chain.

4.1.1 System definition

Performing an MFA is an iterative process, and the steps taken are outlined in figure 6. This time there was already a foundation to build upon and improve. The model from the project work was used to customize a an updated model from Callewaert's work this spring (Callewaert 2017). The generic model is displayed in figure 7. Through-out the work, new data was collected and assumptions changed to make for a better model and more accurately describing the system. Some slack was allowed as the problem desired to solve here was not as precise as possible depiction of the current system, but sane assumptions allowing us to look into the development of a future waste management system.

The system was defined for the household solid waste management of the municipality of

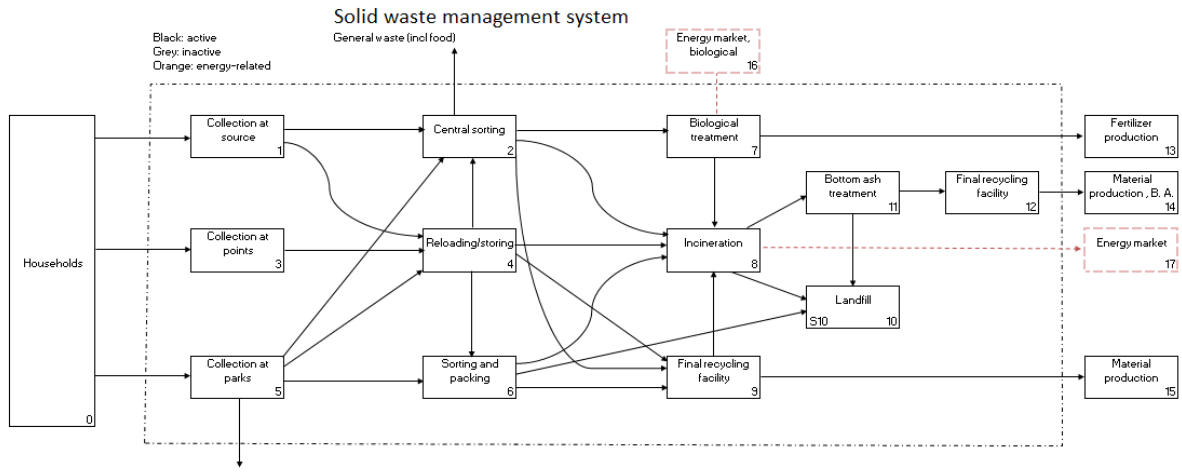

Figure 7: The generic solid waste management system. Flows can be added or removed, processes made active or inactive, depending on implementation of model.

Trondheim. The system encompasses the waste management chain from the collection of waste to the final recycling facilities or final treatment, depending on which waste category or fraction is considered. For a list of processes see the table below. In the table strike-through formatting indicates processes which are inactive for the case-specific model in this study. Italicization indicates that a process is active in a non-reference-scenario. For a description of processes as applied in the model and their corresponding transfer coefficients, see further below in the section on Data and assumption below.

Table 1: List of processes

Number	Process	Note
0	Households	External process
1	Collection at source	
2	Central sorting	
3	Collection at points	
4	Reloading/storage	
5	Collection at parks	
6	Sorting and packing	
7	*Biological treatment*	
8	Incineration	
9	Final recycling facility	
10	Landfill	
11	B. A. T. (bottom ash treatment)	
12	Final recycling facility	
13	*Fertilizer production*	External process
14	Material production, B. A. T.	External process
15	Material production	External process
16	*Energy market, biological treatment*	External process
17	Energy market	External process

The input into the system is the waste generated in households (process 0). The outputs are the matter emitted to the atmosphere (0), fertilizer production (13), material production (14, 15) or energy markets (16, 17). Flows are measured in tons per year, written as t/a. The flows consist of the waste collected by the municipal waste management service provider (TRV). The waste is collected in five categories; plastic waste (plastics), organic waste (organic), residual waste (RW), paper and cardboard waste (P&C), and glass and metal waste (G&M). Each of these categories have their contents listed over eight different and predefined waste fractions. This gives us a matrix of categories by fractions for each flow, as depicted in table 2.

Table 2: The matrix of a flow, this one depicting the results of flow X_{01b}

X01b	plastics	organic	RW	P&C	G&M
glass	0	0	265	3	2080
metal	3	0	190	0	176
plastics	436	0	1177	12	0
organic	17	0	4344	0	0
pap. & card.	28	0	693	3187	0
residual	67	0	2438	19	87
hazardous	3	0	85	0	0
textile	2	0	284	0	0

4.1.2 Model description - the material layer

The generic model was used a base, but the actual flows and selection of categories was customized to fit the case study of Trondheim municipality. The model uses the five waste categories (i) already mentioned, eight waste fractions (j), and three kinds of collection technology (t), see table 3. The model works with layers: the MFA-based mass layer and a simple added energy layer complimenting the material flows based on input transport and process energy data.

Table 3: A list over most important waste distribution/characterization parameters

waste categories (i)	fractions (j)	collection technology (t)
plastics	glass	small bins
organic	metal	underground receptacles
RW	plastics	vacuum system
P&C	organic	
G&M	pap. & cardboard	
	residual	
	hazardous	
	textile	

In figure 8, the generic system definition has been customized to the case study. Processes are all the same, but not all are active. One particularity of note must be explained: Households are defined as process 0, but in general in MFA 0 only denoted external,

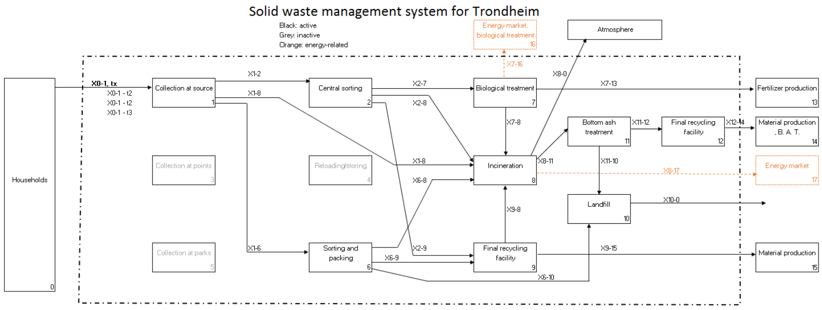

Figure 8: The system definition for waste originating in the municipality of Trondheim. See attachments for the image file in a larger resolution.

Nomenclature

Flow	symbol	unit
Waste flow from a to b	Xab	ton/yr, kg/cap
Waste type i	Wi	ton/yr, kg/cap
Fraction j of waste type i	Wij	%
Collection technology x	tx	%, t/yr, kg/cap

Figure 9: Legend for system definition drawing

non-specific processes. There is another flow going to 0, flow $X_{0\text{-}8}$, but this do not go to households, it is emissions from incineration let into the atmosphere, which could be called 0, as well, but 0 has already been defined as households. Strictly speaking households could be defined as the import process of process 1. Other outflows go to their own external processes to be more able to document the specific outflows.

List of type of data/variables used in the material layer

- waste quantities
- waste sampling
- distribution of waste on different collection technologies
- estimated transfer coefficients, based on technological efficiencies

Data preparation included applying the waste sampling numbers to waste quantities in order to determine the waste composition. Then, based on estimations, the total waste quantities per category were partitioned across the three waste collection technologies. From the waste input in flows X_{01x}, the remaining flows are unknown and determined by applying the given TCs on each process, following the principle of mass-balance as laid out previously. In equation 2, X is a flow, I means input, O means output, k 1 is the number of input flowsand i is a counter.

$$X_O = \mathrm{TC}_i * \sum_{i=1}^{k_1} X_{I,i} \tag{2}$$

The implementation of the model is by a set of scripts written for the MATLAB software, authored by Pieter Callewaert (Callewaert 2017). This code reads the excel sheets, handles the data, performs the MFA calculations according to MFA methods to quantify the system, calculate the KPIs and finally write the results to predefined templated EXCEL sheets. The MATLAB model does a lot of work, but at the same time it is sensitive to errors. Wrong or missing data could either yield illogical results and simply blank results. Also, since the model is based on transfer coefficients only, and not allocation coefficients, all inputs must be known in order to calculate outflows. This does not allow loops and require that the model is linear.[3]

4.1.3 Performance indicators

We want to look at the system's performance when it comes to the recovery of energy and material in the form of recycling of secondary materials, co-generation incineration and the production of waste-derived fuels and fertilizer. A set of performance indicators for the material flow layer has been defined, where theses with the same methodology should use more or less the same definition, see the list below. In addition the energy efficiency of the system is defined as the performance indicator of the energy layer.

List of main performance indicators

- Collection efficiency
- Sorting efficiency
- Material recycling rate
- Company recycling rate, in this case the Trondheim rate
- Overall system energy efficiency

Their definition is common for all three waste projects, because we designed them together, and also because we all use the same model and code. Their wording and equations are collected from a document by Callewaert 2017, who also coded the model according to these formulas. The energy efficiency indicator will be explained later in the section on energy analysis.

Material indicators

As the success of a waste management system in collecting and recycling its materials depends on where performance is measured, each of the material indicators use values from different points in the process chain. The first three indicators follow a similar definition where fractions is the element of scrutiny, while the company rate is calculated somewhat differently. All rates are compared to the amount of waste generated. Comparing the three system indicators gives us information about where in the system losses occur.

Only the materials sorted out for recycling in the collection system are taken into account when calculating the material recycling rate, because what is of interest is how much valuable material is collected of all that is generated. These materials are plastics, organic waste, paper and cardboard (P&C), and glass and metal (G&M).

For the following formulas the following symbols are used:

- i bin or waste category
- j fraction

Vectors of specified processes:

[3]Information collected from Callewaert's project work.

- a collection processes
- b final recycling processes
- c material markets
- d bioenergy markets
- e processes to which the company sends its waste

The model considers the input into the specified processes in each vector.

Collection efficiency

The collection efficiency is defined as *the amount of waste collected correctly over the total amount of household waste generated*. Residual, hazardous and textile waste is not included in this indicator.

$$\eta_{coll} = \frac{\sum_j \sum_a X_{0a,i=j}}{\sum_i \sum_j \sum_a X_{0a,i,j}} \tag{3}$$

With a the collection processes vector and i in the numerator determines the correct bin for fraction j. For all scenarios the correct bin for each fraction is as follows in the table below (table 4 the generic model, the collection processes could be 01, 02 and 03, while in this system we only operate with flow X_{01}, only with several collection technologies.

Table 4: Fractions and their correct bin in collection

j (fraction)	i (correct bin)
glass	G&M
metal	G&M
plastics	plastic
organic	organic
pap. & card	P&C

In order to see how well the collection system works with its bins and selected categories, the collection efficiency is calculated. Residual waste is not a part of the calculation, as the point of the indicator is to measure how well the system source collects the generated valued materials.

Sorting efficiency

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

$$\eta_{sort} = \frac{\sum_i \sum_j \sum_b X_{xb,i,j}}{\sum_i \sum_j \sum_a X_{0a,i,j}} \tag{4}$$

- With b a vector of final recycling processes.

Table 5: Vector b of final recycling processes

#	Final recycling process
7	Biological treatment
9	Final recycling facility
12	Final recycling facility (B. A. T.)

This indicator gives information on the total loss from generated to sorting, fraction-wise.

Material efficiency (Or the material recycling rate, *MRR*)

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

$$\eta_{rec} = \frac{\sum_i \sum_j (\sum_c X_{xc,i,j} + \sum_d X_{xd,i,j})}{\sum_i \sum_j \sum_a X_{0a,i,j}} \tag{5}$$

With c a vector of the material markets and d the bio-energy markets. This means that all organic waste outputs from the biological treatment are considered recycled material.

Table 6: Vector c of final recycling processes, output to which is considered to be recovered material

#	Material market process
13	Fertilizer production
14	Material production
15	Material production

Table 7: Vector d of bio-energy markets

#	process
13	Fertilizer production
16	Energy market, biological

This indicator show the share of generated material which has been processed into secondary material amounts obtained at the end of the recycling process. As for the assumption of all organic material input to biological treatment process, this is a simplification. A lot of the mass input is turned into another useful product, the biofuel.

Company specific recycling rate (or company rate for short)

$$\eta_{comp} = \frac{\sum_i \sum_j \sum_e X_{xe,i,j}}{\sum_i \sum_j \sum_a X_{0a,i,j}} \tag{6}$$

With e as a vector of the processes to which the company sends its waste.

The company specific recycling rate looks at the total collected waste in valuable waste categories. For this particular case it also does an attempt at emulating the way material recycling reporting is done in the municipalities, at least the municipality of Trondheim, to compare with their own reported number.The indicator measures where the company turns over the custody of the waste to another actor.

The company rate is different from the collection rate in that it looks further downstream depending on what facilities the company owns, and in that it considers the whole content of categories and not only the specific fractions in their correct bins.

Assumptions

Table 8: Company process vector e. What is sent to the listed processes are considered "materially recycled"

category	process
plastics	9, recycling
organic	7, biological treatment
P&C	6, sorting and packing
G&M	6, sorting and packing

Also, these are the differences between this rate and the rate resulting from the municipal KOSTRA-data, as laid out in the case study chapter. They are likely to make the company rate produce different numbers than those of the municipality. This indicator does not consider

- any collected waste from the MRF, even if it's the same categories, plastic or glass (defined categories). extra quantities of waste collected at their public MRF
- any additional waste categories beyond those defined in the model, i. e. e-waste, textiles, green waste, etc.

It does consider

- loss downstream
- gains downstream

4.2 Energy analysis and the energy layer

Waste management is a high consumer of energy in transporting, processing and sorting waste, but for some processes, it is a net producer of energy. To study the energy consumption in the model, an energy analysis has to be performed. This was performed by adding an energy layer on top of the MFA system. The energy layer operates with two types of energy consumption; process and transport energy; two types of energy production: heat and biogas; and one stock energy the feedstock energy in the waste itself.

List of type of data used in the energy layer

- process energy

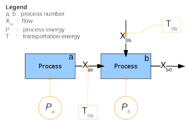

Figure 10: The system definition for waste management originating in the municipality of Trondheim. See attachments for the image file in a larger resolution.

- transportation data
  - distance
  - energy intensity of distance per ton

The energy flows were calculated by applying process and transportation energy values to the material flows. Figure 10 tries to illustrate this. The process energy value is applied to all inputs to a process. The transportation values are applied on a per-flow basis. To get the total energy consumed in relation to a process, all transportation energy flows inputs are added to the process energy consumed.

4.2.1 Process energy

Process energy is the energy consumed by activity defined as a process in the model.

$$\text{Processenergy}\left(\frac{kWh}{yr}\right) = \text{Weight}_{p,i}\left(\frac{t}{yr}\right) \cdot \text{Energy requirement}_{p,i,f}\left(\frac{kWh}{t}\right) \tag{7}$$

Process energy coefficients are entered as kWh per ton, then the process energy results are calculated based on the MFA flow values: the total tons of waste per category entering the process.

4.2.2 Transportation energy

The calculation of transportation energy is based on the distance travelled per waste category and per process , and on the energy intensity of the mode of transport per ton kilometer. In this way, each process has its own a coefficient of kWh per waste category, although most of them are identical. For process 1, collection technology also plays a role. For instance, if the transport of 100 t of paper from process a to process b utilizes a truck with a known energy intensity of 0.35 kWh/tkm and drives over a distance of 200 km in total back and forth, the resulting energy consumed is calculated to be 100 t x 0.35 kWh/tkm x 200 km = 7 000 kWh.

For the equations for energy consumption, energy intensity and transport energy, see the attached document called “common definitions model.docx”

4.2.3 Energy efficiency indicator

The last of the key performance indicators is the system-wide energy efficiency, selected as the indicator for the energy layer. The energy efficiency takes into account energy consumed in processes and by transportation work, and includes energy delivered as heat from the incineration plant or produced as biogas from the biological treatment. It also considers the chemical energy inherent in the waste, the so-called feedstock energy.

Some assumptions had to be made in order to calculate the energy efficiency. For this specific implementation, losses beyond the efficiency of the processes within the system boundary are not accounted for. This means that losses in utilizing heat and energy products outside of the system are not included and means that the resulting efficiency results will be higher than if this was to be considered. An example is the efficiency in the district heating system fed by incineration plant heat, or the loss of volume when refining biogas from the biological treatment for use in vehicles. Potential energy savings through the substitution of new material production are also not a part of the calculations.

The definition of energy efficiency

$$\eta_{energy} = \frac{\text{Biogass out} + \text{Energy out}}{\text{Transport energy} + \text{Process energy} + \text{Calorific value waste input}} \tag{8}$$

In calculating this energy efficiency indicator (8, the energy delivered by the system, either in the form of fuelstock, heat or other forms, is divided by the energy available in the feedstock (the potential), plus the sum of energy spent during transportation and treatment processes.

Biogas energy and energy out are both calculated by equations which can be find in the attached document called “common definitions model.docx”

4.3 Data and assumptions

This part will cover the source of data used, data estimations and the assumptions in using them in my model. There is data which is directly used and data which is used to perform estimates.

4.3.1 Waste generation

The data foundation of the model are waste quantity numbers from the municipal waste management company, coupled with supplied and estimated waste sampling numbers. The first decision was to decide what waste categories to include and naturally it occurred to simply copy the categories TRV collect, also because that is the system we wish to model. In addition to those four, an organic category was added because of an interest in modelling future scenarios with source separation of organic waste. In contrast to in my project assignment, the household waste recycling center (MRF) has been excluded from the model. This means we are exlusively looking at the mass flow and energy inherent in the logistics of TRV’s operations.

List of waste categories (abbreviations in parentheses)

- plastics
- organic waste (organics)

Estimated future waste quantities									
Year	plastics	organic	RW	P&C	G&M	organic in RW	sum	change	RW adjusted
2016	1351,7	-	30391,3	8705,7	2343,4	13931,4	42792,1		
2020	1527,1	6424,9	30469,5	8449,4	2445,8	13967,2	42891,7	0 %	24044,6
2025	1758,3	6372,2	30219,6	8046,9	2550,8	13852,7	42575,6	-1 %	23847,4
2030	2017,6	6297,9	29867,3	7636,9	2650,9	13691,2	42172,8	-1 %	23569,4

Figure 11: Applied waste quantities for each category and year

- residual waste (RW)
- paper and cardboard (P&C)
- glass and metals (G&M

4.3.1.1 Future projection of waste quantities

Future waste quantities was calculated based on a simple change from selected year to selected year, as illsutrated in figure 11

4.3.2 Sampling analyses

Waste categories as collected and reported by waste management companies do not contain only what their name indicate. There is a high share of contamination in the residual waste category. By applying these waste sampling rates to the quantities, a more accurate picture of the waste composition will be given. The model then diverts the different fraction in each category by the use of TCs specific to both waste categories (determine their location) and fractions (determine properties and final fate).

For organic waste, it is the system of green bags which have been sampled. As for the material layer, there seemed to be some relation between type of colleciton technology and composition and purity of waste inputs, but such assumptions would require a closer examination of national sampling analysis and confounding factors such as type of dwellings and was not subject of study for this thesis. A possible side effect of spacious containers could be less missorting in the collected waste, which also is something alluded to in the waste sampling reports.

4.3.2.1 Defining the waste fractinos

In the waste sampling reports differing number of categories was used, aggregated into a set of eight fractions, see the list below. The fractions are aggregated based on what main categories would mostly correspond to the collected waste types. In addition, there is also the value of all three modelling the same fractions, even if it is not necessary for the model. For a higher resolution it would make sense to divide paper into paper and cardboard, and metals into aluminum, steel and other metals. A further simplification is present by the collapsing of three economic paper categories paper, cardboard and beverage cardboard-based packaging, as all these three are sorted out and shipped for recycling at three different facilities.

WASTE SAMPLING

Base scenario	ref, fix	fix	ref	fix	ref, fix	ref, fix
	Plastics	**Organic green bags**	**Residual**	**Residual adjusted**	**Paper & cardboard**	**Glass & metals**
glass	0,00 %	0,10 %	2,80 %	3,55 %	0,08 %	88,78 %
metals	0,60 %	0,08 %	2,00 %	2,53 %	0,00 %	7,50 %
plastics	78,30 %	0,63 %	12,42 %	15,74 %	0,37 %	0,00 %
organic	3,10 %	94,40 %	45,84 %	31,37 %	0,00 %	0,00 %
paper	5,00 %	0,24 %	7,31 %	9,26 %	98,93 %	0,00 %
residual/other	12,10 %	4,55 %	25,73 %	32,61 %	0,60 %	3,70 %
hazardous	0,50 %	0,00 %	0,90 %	1,14 %	0,01 %	0,00 %
textiles	0,40 %	0,00 %	3,00 %	3,80 %	0,01 %	0,00 %
SOURCE:	Mepex 2015 TRV	Mepex 2015 ROAF	Mepex 2015 TRV	calc	COWI 2012 Trondheim	@solberg

Figure 12: Waste sampling

List of what constitutes the defined waste fractions

- glass: the fractions glass and metals is majorly packaging, but downstream non-packaging metal might appear in central sorting, for instance.
- metals: same as above
- plastics: contain mainly packaging.
- organic: plants and tissue paper
- paper and cardboard: itself
- residual waste: soiled material, ceramics,Residual waste is ceramics, diapers
- hazardous waste: batteries, electronics, chemical containers
- textiles: leather, textiles, fabric

4.3.3 Collection technologies

For the system input of waste from households to collection (flow X_{01}), part of the distribution of the waste quantities relates to the partitioning of waste on the different collection technologies. Collection technologies impacts the results purely in the energy layer, where larger receptacles require less frequent collection. For simplicity underground receptacles and the bottom-holed bins are considered the same, as both are collected by the same truck.

Collection technology (Norwegian term in parentheses)

- two-wheeled plastic bins (småbeholdere)
- underground receptacles: molok and metal-deck (bunntømte og nedgravde)
- mobile and central vacuum systems (mobilt og stasjonært avfallssug)

4.3.4 Process decriptions and transfer coefficients

Here assumptions will be explained and data referenced for the TCs of outflows from each process. The TCs is what determine the efficiencies of the processes and determine the loss of material throughout the system. The TCs of the reference scenario is described, for the other scenarios, see the section on scenarios further in the report.

Due to limitations in the implementation of the model no stocks are modelled. Process 10, the landfill which typically following MFA methodology would be modelled as a stock instead has its inflow modelled as an outflow, X_{10-0} for balancing the whole system out. The alternative would be to make it flow to a process 18 outside of the system boundary, to separate it from process 0 which is defined as households.

Some processes have been kept in which are inactive and have been left out for this application of the model. This is a consequence of using a generic and dynamic model to keep model consistency across our three projects. These are processes 3, 4 and 5. They are left empty and connected, for the model code to run properly, since they are still a part of the computer code.

For a complete table of TCs for all scenarios and more comments, see the attached file "data-assumptions.xlsx".

1. Collection

The collections process symbolizes the collection of waste at households and the transfer to the next processes such as central sorting or reloading and sorting. All TCs here are binary, as a collected waste fraction only go one place and there is an assumption of no loss. What quantities of each category going into collection are decided by waste quantities generated.

G&M should by the generic model definition enter the system through process 3 and not 1, but this was discovered late in the modelling process and was judged to not be of any practical importance.

In the reference scenario plastics, G&M and P&C are send to 6 - sorting (TC1-6) and residual waste go to 8 - incineration (TC1-8). TC1-2 is active for the fix, perfect and improved scenarios.

For the first flow, X01, TCs are not used, as the waste quantities are known and fed directly into the model, as descbied in the section on waste generation and sampling analyses.

2. Central sorting

The point of a central sorting plant is to direct and efficiently sort out all valuables in a mixed waste stream. Failure to sort is caused to contamination of waste, or properties which the technology cannot yet handle.

As for sorting rates (TC2-9), no glass is recovered. Again, based on (RoAF 2015), rates are as shown in table /figuref. For simplicity, all rates are entered for all categories. Losses are sent to incineration, and TC2-8 are set based on what is left from TC2-7 and TC2-9.

T29	pla	org	RW	P&C	G&M
	0,00	0,00	0,00	0,00	0,00
	0,90	0,00	0,90	0,90	0,90
	0,42	0,00	0,42	0,42	0,42
	0,00	0,00	0,00	0,00	0,00
	0,50	0,00	0,50	0,50	0,50
	0,00	0,00	0,00	0,00	0,00
	0,00	0,00	0,00	0,00	0,00
	0,00	0,00	0,00	0,00	0,00

Figure 13: TC29 for the fix scenario

Transfer Coef	T68	pla	org	RW	P&C	G&M
glass		1,00	0,00	0,00	1,00	0,00
metal		1,00	0,00	0,00	1,00	0,00
plastics		0,02	0,00	0,00	0,02	1,00
organic		1,00	0,00	0,00	1,00	1,00
pap. & card.		0,00	0,00	0,00	0,00	1,00
residual		1,00	0,00	0,00	1,00	1,00
hazardous		1,00	0,00	0,00	1,00	0,00
textiles		1,00	0,00	0,00	1,00	1,00
Transfer Coef	**T69**	**pla**	**org**	**RW**	**P&C**	**G&M**
glass		0,00	1,00	1,00	0,00	1,00
metal		0,00	1,00	1,00	0,00	1,00
plastics		0,98	1,00	1,00	0,98	0,00
organic		0,00	1,00	1,00	0,00	0,00
pap. & card.		1,00	1,00	1,00	1,00	0,00
residual		0,00	1,00	1,00	0,00	0,00
hazardous		0,00	1,00	1,00	0,00	0,50
textiles		0,00	1,00	1,00	0,00	0,00

Figure 14: TC68 and 69 for all scenarios

It is not strictly needed, the model could calculate the numbers itself. Metals have the highest sorting rate at 88%. Plastics are surprisingly low at 36% only.

6. Sorting and packing

7. Biological treatment

Process 7 is named biological treatment. In this system it is an fermentation process, but for another model it could very well be a composting process.

8. Incineration

Most of the mass in this particular case is sent to a specific incineration plant, but there are some waste inputs from sorting of paper, plastic, organic material and recycling. Ther fore, the selected efficiency should reflect an average of incineration plants in Norway or

Transfer Coef	T78	pla	org	RW	P&C	G&M
glass		1,00	1,00	1,00	1,00	1,00
metal		1,00	1,00	1,00	1,00	1,00
plastics		1,00	1,00	1,00	1,00	1,00
organic		1,00	0,01	1,00	1,00	1,00
pap. & card.		1,00	1,00	1,00	1,00	1,00
residual		1,00	1,00	1,00	1,00	1,00
hazardous		1,00	1,00	1,00	1,00	1,00
textiles		1,00	1,00	1,00	1,00	1,00
Transfer Coef	**T713**	**pla**	**org**	**RW**	**P&C**	**G&M**
glass		0,00	0,00	0,00	0,00	0,00
metal		0,00	0,00	0,00	0,00	0,00
plastics		0,00	0,00	0,00	0,00	0,00
organic		0,00	0,99	0,00	0,00	0,00
pap. & card.		0,00	0,00	0,00	0,00	0,00
residual		0,00	0,00	0,00	0,00	0,00
hazardous		0,00	0,00	0,00	0,00	0,00
textiles		0,00	0,00	0,00	0,00	0,00

Figure 15: TC7 for all scenarios

Transfer Coef	T811	pla	org	RW	P&C	G&M
glass		0,97	0,97	1,00	0,97	0,97
metal		0,94	0,94	0,94	0,94	0,94
plastics		0,08	0,08	0,08	0,08	0,08
organic		0,01	0,01	0,01	0,01	0,01
pap. & card.		0,06	0,06	0,06	0,06	0,06
residual		0,19	0,19	0,19	0,19	0,19
hazardous		0,80	0,80	0,80	0,80	0,80
textiles		0,04	0,04	0,04	0,04	0,04

Figure 16: TC811 for all scenarios

Transfer Coef	T98	pla	org	RW	P&C	G&M
glass		1,00	1,00	1,00	1,00	0,10
metal		1,00	1,00	0,05	1,00	0,05
plastics		0,20	1,00	0,20	1,00	1,00
organic		1,00	1,00	1,00	1,00	1,00
pap. & card.		1,00	1,00	0,05	0,05	1,00
residual		1,00	1,00	1,00	1,00	1,00
hazardous		1,00	1,00	1,00	1,00	0,50
textiles		1,00	1,00	1,00	1,00	1,00
Transfer Coef	**T915**	**pla**	**org**	**RW**	**P&C**	**G&M**
glass		0,00	0,00	0,00	0,00	0,90
metal		0,00	0,00	0,95	0,00	0,95
plastics		0,80	0,00	0,80	0,00	0,00
organic		0,00	0,00	0,00	0,00	0,00
pap. & card.		0,00	0,00	0,95	0,95	0,00
residual		0,00	0,00	0,00	0,00	0,00
hazardous		0,00	0,00	0,00	0,00	0,50
textiles		0,00	0,00	0,00	0,00	0,00

Figure 17: TC9 for all scenarios

Transfer Coef	T1112	pla	org	RW	P&C	G&M
glass		0,00	0,00	0,00	0,00	0,00
metal		0,60	0,60	0,60	0,60	0,60
plastics		0,00	0,00	0,00	0,00	0,00
organic		0,00	0,00	0,00	0,00	0,00
pap. & card.		0,00	0,00	0,00	0,00	0,00
residual		0,05	0,05	0,05	0,05	0,05
hazardous		0,20	0,20	0,20	0,20	0,20
textiles		0,00	0,00	0,00	0,00	0,00

Figure 18: The planned TC1112 for all scenarios

Europe. Therefore, the selected efficiency of plant. Statkraft varme rarely achieves more than 80%. Lower plants abroad have even lower rates.

9. Final recycling facillity

10. Landfill

All TCs are 1, sent from process 10 to process 0.

11. Bottom ash treatment

Bottom ash treatment is not really taken into account, other than the sorting of metals from the bottom ash. Bottom ash sorting utilizes the same technologies which would be used in a central sorting facility for extracting metals. What is extracted are ferrous metals, non-ferrous metals and aluminum.

Figure 19 is the set of TCs I accidently applied to the model, which then produced no results for process 12 and downstream.

Transfer Coef	T1112	pla	org	RW	P&C	G&M
glass		0,00	0,00	0,00	0,00	0,00
metal		6,83	0,00	336,90	0,00	5,61
plastics		0,00	0,00	0,00	0,00	0,00
organic		0,00	0,00	0,00	0,00	0,00
pap. & card.		0,00	0,00	0,00	0,00	0,00
residual		2,26	0,00	71,08	0,42	0,45
hazardous		1,61	0,00	43,01	0,12	0,00
textiles		0,00	0,00	0,00	0,00	0,00

Figure 19: The wrongly applied TC1112 for all scenarios

T29	pla	org	RW	P&C	G&M
glass	0,00	0,00	0,00	0,00	0,00
metal	0,90	0,00	0,90	0,90	0,90
plastics	0,70	0,00	0,70	0,70	0,70
organic	0,00	0,00	0,00	0,00	0,00
pap. & card.	0,95	0,00	0,95	0,95	0,95
residual	0,00	0,00	0,00	0,00	0,00
hazardous	0,00	0,00	0,00	0,00	0,00
textiles	0,00	0,00	0,00	0,00	0,00

Figure 20: TC12-0 for all scenarios

12. Recycling (of bottom ash)

4.3.5 Process energy data

The process energy is the energy consumed by the defined processes as they are storing, transferring or transforming the input material. Data has been hard to find and most is based numbers on personal communication with facility employees. Some are calculated from values from the life-cycle analysis inventory database ecoInvent. All scenarios apply the same process energy values. Values are given in kWh/t/a. Efficiency of incineration plant has been considered.

Feedstock energy

To calculate the feedstock energy in the waste, the values used by Callewaert (2017) was used for consistency, see table 21.

4.4 Scenarios

The starting point of the model is the reference scenario (ref for short) where gathered data was used to quantify the waste flows for 2016. It was further extended to 2020, 2025 and 2030. The reference scenario tries to replicate the current situation of mass and energy flows in Trondheim municipal solid waste management. It follows the case description closely. As time progresses no changes to the waste management system is

Feedstock energy source: Christensen2010

fraction	LHV (kJ/kg)	note
glass	-73	
metal	-147	
plastics	20144	
organic	1912	
pap. & card.	6440	
residual	7650	weighted average (Callewaert2017
hazardous	10000	assumption (Callewaert2017)
textiles	11789	

Figure 21: Table of feedstock energy values

implemented at all. In practice this will not feasible due to issues in collecting increasing quantities of waste, and also new legislative requirements (both as spelled out in the case chapter, section), but the reference scenario serves as a status quo to which the other scenarios are compared. For a list of TCs and other data assumptions used, please be referred back to the Data and assumptions section of the current chapter.

4.4.1 Scenario development

In order to explore the impact of measures and policy changes and the dynamics of the system, a set of four more scenarios were designed based on a variety of assumptions. All of them were run for the years 2020, 2025 and 2030, in order to see the development of efficiencies as waste quantities slowly increase, which is interesting in the context of waste prevention. Along the time-line there is no change of assumptions except for the amount of waste generated based on population changes. Scenarios are thus modelling impacts along two dimensions: different measures on one line and the passage of time through changing waste quantities on the other. Three of the scenarios, both perfect and the burn scenarios, explore the extremes, while the fix scenario tests measures to reach material recovery targets. See the list below for a short summary of each, and table 9for main differences.

List of selected scenarios:

- fix scenario: to check the effect of source segregating organic waste and the usage of a central sorting facility (CSF)
- perfect central sorting: to check the effect of improving the sorting efficiency of the CSF
- perfect household sorting: to check the effect of increased household solid waste sorting efficency
- burn: to check the effect of sending most waste to incineration and heat production

Table 9: (Table of key scenario measures)

	ref	fix	perf-c	perf-h	burn
based on	-	-	fix	fix	ref

	ref	fix	perf-c	perf-h	burn
collection of organic waste and central sorting	-	y	y	y	-
improved household sorting	-	-	y	y	-
improved central sorting	-	-	y	y	-
number of curbside receptacles	3	2	2	2	3
compression-related fuel consumption increase	-	y	y	y	-

4.4.2 Fix

Fix describes the municipality's intention to upgrade its waste management and provide a fix to the challenges of population growth and increased targets of material recycling. By 2020 the municipality will see the implementation of source segregation of organic waste and the construction of a local central sorting facility. Also, a higher share of waste collection now takes place with the help of out-of-sight and space-saving technologies such as underground receptacles and vacuum systems. As laid out in the case description, the residual and organic waste will be sorted into separate, distinctly colored bags, while plastic will be tossed directly into the same receptacle. Paper and cardboard continue to have their own bin due to the value of the materials. The bags are sorted optically at the central sorting facility, where the organic waste goes directly to biological treatment, while residual waste bags are ripped open and sorted together with the incoming plastic.

The objective is to recover more of the waste material, not only the organic subfractions which was not recovered before, but additional quantities of metals, paper and plastics which otherwise would end up being incinerated. Lastly, underground solutions and vacuum systems are hoped to lower the transport work required to service the waste.

As for the model implementation, the transfer coefficients (see the process description on central sorting) used are improved compared to those reported by RoAF. It is assumed that the technology will improve, helped by the continous reporting of problems RoAF has seen in its facility. A proposal from the municipality (Knut Jørgen Bakkejord, by personal communication) is design for easier cleaning of the facility, which could reduce the loss of material due to soiling (in particular plastics). One issue with central sorting is that the green bags containing the organic waste are somewhat prone to ripping, increasing loss of both organic waste and other fractions due to soiling. A realted issue is that the use of bags and bags sorting are more vulnerable to compression during collection.

Even if the fix scenario actually will have two receptacles, they will continue to be modelled as separate wastes, with the change happening in the transport/energy layer. Plastic distance is kept as is, while organic gets its share from RW distance based on how much is diverted out. This is a gross simplification.

Parameter changes from the reference scenario * separation of organic waste in green bags (using the green bags sampling analysis) * the use of a central sorting facility, which is an improved version of RoAF's * collection system: reduction of curbside receptacles to two, G&M continues as a public collection point * Container 1: residual waste in bag, plastic in bag, organic waste in green bags * Container 2: paper and cardboard * 20% higher fuel use per ton due to less compression because of bags

T29	pla	org	RW	P&C	G&M
glass	0,00	0,00	0,00	0,00	0,00
metal	0,90	0,00	0,90	0,90	0,90
plastics	0,70	0,00	0,70	0,70	0,70
organic	0,00	0,00	0,00	0,00	0,00
pap. & card.	0,95	0,00	0,95	0,95	0,95
residual	0,00	0,00	0,00	0,00	0,00
hazardous	0,00	0,00	0,00	0,00	0,00
textiles	0,00	0,00	0,00	0,00	0,00

Figure 22: Central sorting transfer coefficients

4.4.3 The two "perfect" scenarios

These two scenarios looks at what happens to the system efficiencies when households and the CSF have a perfect or - more precisely described - as close as can be to perfect sorting efficiency. They are based on the fix scenarios and will investigate the upper limits of the system. The results will reveal the potential gains from improving each efficiency.

4.4.3.1 Perfect central sorting (perf-c)

Central sorting facilities work worse than expected. Here the transfer coefficients are improved based on what technologically feasible. The loss of green bags (organic waste) is set to zero based on the assumptions that the bags are made of a stronger material, and that there is a separate line for green bags (Knut Jørgen Bakkejord, by personal communication). To achieve such high TCs, a minimum of soiling from stray green bags must occur.

TCs can be seen in figure 22. According to Syversen and Bjørnerud (2016b) 70% of plastics have the potential to be sorted out in a CSF. As for the organics waste category, all green bags entering are sent to biological treatment. For metals and paper & cardboard the high efficiency is based on the assumption that soiling from missorted organic waste is at a minimum, and inspired by the high efficiency in recycling facilities (process 9).

Based on the fix scenario, parameter changes:

- the central sorting facility has a highly improved efficiency for three fractions and one waste category.
  - green bags loss is 0%

4.4.3.2 Perfect household sorting (perf-h)

PERF HOUSEHOLDS SAMPLING ANALYSIS	plastics	organic	RW	P&C	G&M
glass	0,00 %	0,05 %	5,27 %	0,07 %	87,71 %
metals	0,35 %	0,04 %	3,83 %	0,00 %	8,74 %
plastics	92,25 %	0,30 %	17,40 %	0,33 %	0,00 %
organic	1,05 %	97,76 %	3,65 %	0,00 %	0,00 %
paper	1,01 %	0,12 %	8,26 %	99,05 %	0,00 %
residual/other	4,80 %	1,74 %	53,58 %	0,53 %	3,54 %
hazardous	0,29 %	0,00 %	1,85 %	0,01 %	0,00 %
textiles	0,24 %	0,00 %	6,15 %	0,01 %	0,00 %
	100,0 %	100,0 %	100,0 %	100,0 %	100,0 %

Figure 23: Assumed household solid waste sampling analysis

How efficient households are in separating their waste is likely to have a huge impact on the system, as it laying the foundation for all the downstream processes and flows. This scenario assumes that as education takes hold in the populace, increased consciousness about resource conservation and knowledge on the importance waste recycling leads to a higher sorting efficiency.

The method of calculating these new TCs (figure {fig:samplingHouseholds} is simply a movement of missorted material from the residual waste categories to their correct categories. Inspiration for the levels of contamination in the residual and plastics waste categories was taken from the Mepex waste sampling report (Syversen and Bjørnerud 2016a). For Nord-Trøndelag (the Northern region), residual waste contained 15.3% organic waste, 4.9 paper and cardboard, ca. 12% plastics, 5% glass and 5% metal. Their plastics category was sampled to contain less than 1% organic waste, ca. 5-11% residual waste and less than 1% paper and cardboard. The selected organic contamination in RW is probably unrealistically low, but on the other hand, it is a way to study the effects of higher organic source segregation efficiency.

Based on the fix scenario, parameter changes:

- contamination rates in each waste category are low, only a minimum of recyclable materials ends up in the residual waste

4.4.4 Burn - a simplified downstream

After testing improved sorting rates, I thought it would be interesting to check out the other side of the coin. Here the impact of less material recovery on energy efficiency of system is investigated. One seeks to minimize energy spent on transport and sorting of waste and will hit the lower limits of the system when it comes to material recovery rates. The difference from this to the reference scenario is that paper and cardboard - a currently both profitable and sustainable recycling material - is sent to the incineration plant. Only metals and glass are separated out, mainly due to the values in the metal and

parameter/explanation	flow	change	fraction	category
improved sorting facility, plastic, all categories	T16	1 %	plastics	
improved central sorting facility, organic waste	T27	1 %	organic	organic
worse P&C recycling	T98	1 %	pap. & card.	
worse plastics recycling	T98	1 %	plastics	
worse metals recycling	T98	1 %	metal	

Figure 24: Parameters changed

the futility of burning what is essentially rocks. Apparently, the material efficiency will be quite low, but what will happen to the energy efficiency of the system? Any incineration plant capacity issues are not taken into account. The collection will be simpler, when previous three receptacles are reduced to a single, larger one curbside.

Based on the reference scenario, parameter changes:

- Transfer coefficients from 1 to 8 (Collection to Incineration) will be set to 1 for all waste categories except for glass and metals.

4.5 Sensitivity analysis

The purpose of a sensitivity analysis is to investigate how changes in parameters will affect the outcome of the modelling. Input variables and assumptions are deliberately changed to test the robustness of the model and reveal relationships between input and output variables (Seldal 2014). In this study the method of changing a single parameter and keeping all other parameters fixed was used (Seldal 2014).

Three transfer coefficients were selected for sensitivity analysis, T16, T27 and T98, with regards to different fractions. Table 24 shows the selected parameters for analysis. Analysis was performed for scenarios ref2020 and fix2020, because these are earliest years available for the two main scenarios, and the variation through time-series have been observed to be low.

As seen in RoAF (2015) currently there is quite the loss at the central facility. To understand how this impacts sydtem performance, it is important to explore the effect of reduced loss and missorting of materials at a central sorting facility. The same goes for the simpler sorting facility (only plastics and paper) in the reference scenarios. At the same time the effect on indicators of less waste sent to incineration is checked, as waste is diverted from incineration to recycling. The objective to test the sensitivity of worse recycling is to see the system impact of worse technology downstream. Otherwise, the effect of the quantity of input to the system and household sorting efficiency will be explored throughout the time series of the ref and fix scenarios, as well as through the perfect household sorting-scenario.

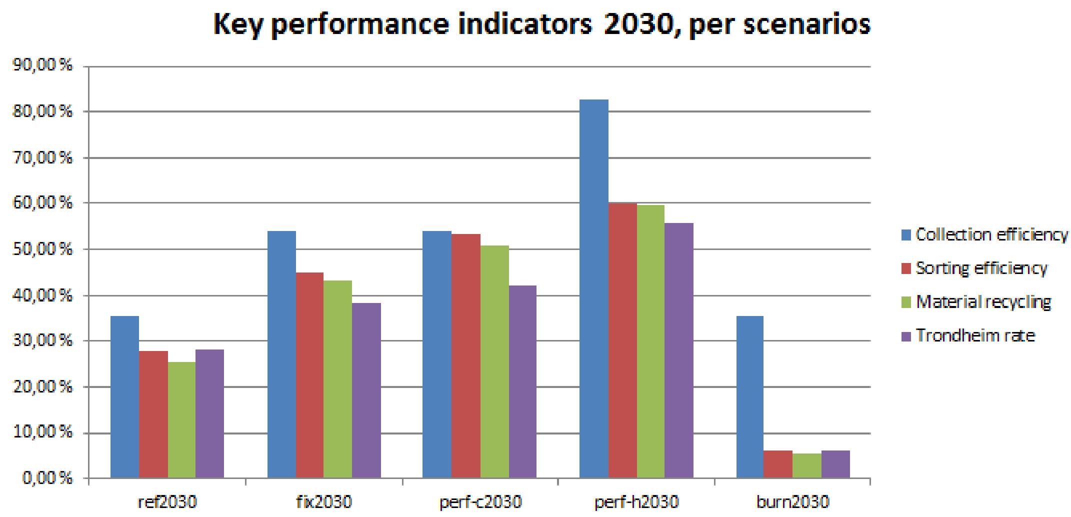

Figure 25: Performance indicators for each scenario

5 Results

In this section the results from running the scenarios are presented in a score of figures. It must be noted that the results are calculated from a series of assumptions both in the model and in calculating the data itself, and therefore it is of importance to keep this in mind when evaluating the results.

5.1 Scenario results

The focus in the results will be on comparing the reference scenario of 2016 and the other scenarios run in 2030, the last year, with only some light shone upon development over time in a separate section. The cause of this is that the additional years of the scenarios produce almost identical results.

5.1.1 Reference scenario

We start out by looking at the reference scenario for 2016, describing the results for the current waste management system in Trondheim with the latest data. In table 26 the performance of the material layer and the energy layer is displayed, the material efficiencies broken up into fractions and the energy indicators into types of energy. For a better visualization of the material indicators, figure 25 displays the four calculated material layer performance indicators for each scenario for the year 2030. The table for ref2030 is provided, too, for comparison (figure 27).

The reference scenario has a material recycling rate of 29,8 %, which as much as 35% short of the 2030 target. It is also roughly 3 percent lower than the MRR as calculated by Trondheim. In fact, none of the scenarios makes the target of 65% by 2030. Also, there is a ca. 5 % loss of material from sorting to material recycling, making the reference scenario second to worst in losing sorted material downstream.

ref2016

MATERIAL INDICATORS

Material	Collection	Sorting	Recycling	Trondheim
glass	70,8 %	70,8 %	63,7 %	71,0 %
metal	22,2 %	22,2 %	21,1 %	22,2 %
plastics	21,8 %	13,5 %	10,5 %	13,8 %
organic	0,0 %	0,0 %	0,0 %	0,0 %
pap. & card.	79,0 %	74,4 %	70,2 %	79,6 %
residual	0,0 %	0,0 %	0,0 %	1,7 %
hazardous	0,0 %	0,0 %	0,0 %	0,3 %
textiles	0,0 %	0,0 %	0,0 %	0,1 %
Aggregated	35,6 %	25,8 %	23,8 %	27,5 %

ENERGY INDICATORS

Energy (kwh)	
Feedstock	2,70E+08
Transport	7,14E+07
Process	1,80E+07
Energy out	4,97E+07
Efficiency	13,82 %

Figure 26: Performance indicators for ref2016

ref2030

MATERIAL INDICATORS

Material	Collection	Sorting	Recycling	Trondheim
glass	73,6 %	73,6 %	66,3 %	73,8 %
metal	24,6 %	24,6 %	23,4 %	24,6 %
plastics	29,7 %	18,3 %	14,4 %	18,5 %
organic	0,0 %	0,0 %	0,0 %	0,0 %
pap. & card.	76,8 %	72,8 %	68,2 %	77,7 %
residual	0,0 %	0,0 %	0,0 %	1,8 %
hazardous	0,0 %	0,0 %	0,0 %	0,3 %
textiles	0,0 %	0,0 %	0,0 %	0,1 %
Aggregated	35,5 %	25,3 %	23,2 %	26,9 %

ENERGY INDICATORS

Energy (kwh)	
Feedstock	2,72E+08
Transport	7,10E+07
Process	1,70E+07
Energy out	5,03E+07
Efficiency	14 %

Figure 27: Performance indicators for ref2030

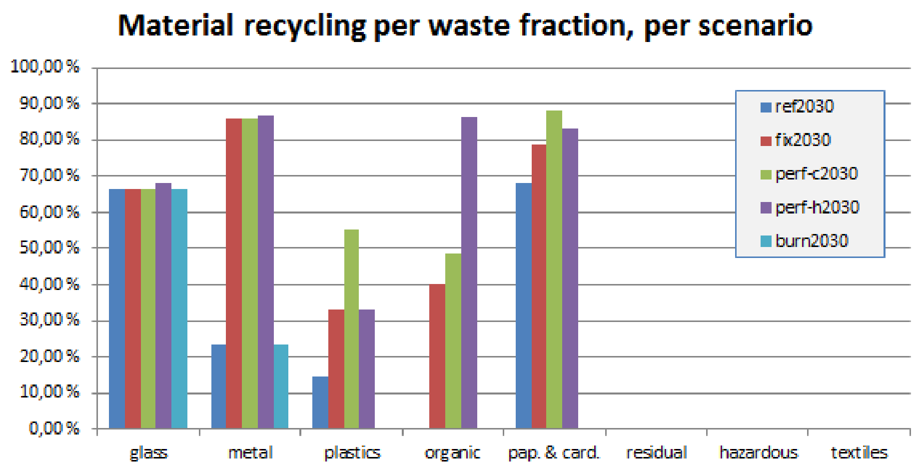

Figure 28: Material recycling per waste type for each scenario

The aggregated MRR for Trondheim is calculated to be 23,8%, which is lower than the number reported by the municipality - , as mentioned in the case study. All these indicators have been aggregated by weight. The model calculated recycling rate - the Trondheim material recycling efficiency, calculated with the methods the municipality uses, also corresponds nicely to their reported number. The efficiencies from collection to recycling sees a drop in value, meaning there is a loss downstream. The largest loss happens during sorting, indicated by the difference between the collection and sorting efficiency. Looking closer at the fraction indicators we see that most of this loss stems from loss of plastic. Going from sorting to recycling efficiency, the largest loss occurs in the glass and paper fractions. No drop in the efficiency rates from collection to sorting means that no sorting and losing process takes place in the transfer of waste from collection to sorting processes.

Going back to the table in figure 26, fraction-wise, material recycling is highest within glass and paper fractions, which is not surprising due to the low loss in the TC defined for processing of these fractions. Metals, on the other hand, have a low recycling rate, but this is due to a low collection in the first place, because otherwise the loss going downstream is very low. In sum, the loss from collection to MRR is caused by loss in the plastics and paper fractions.

The recycling per fraction for ref2030 can be seen compared to the other scenarios in figure 28, which displays directly the impact of scenario assumptions on each fraction. The material recycling of metals and plastics in the reference scenario is significantly lower than for the scenarios with a central sorting facility, which increases the sorting efficiency compared to the collection efficiency rate. Also it has to be noted that in this figure the fractions residual, hazardous and textiles fractions are zero or as close as to be invisible in this figure because no materials have been recovered due to an error when applying the TC-coefficients, stopping the model from calculating anything downstream of process 11.

In this model, waste is treated either by incineration, biological treatment or material recycling. Figure 29 shows the distribution of waste on each treatment method for each scenario. The values have been adjusted for the double counting of flows sent to incineration from recycling and biological treatment. For the reference scenario 74.5%

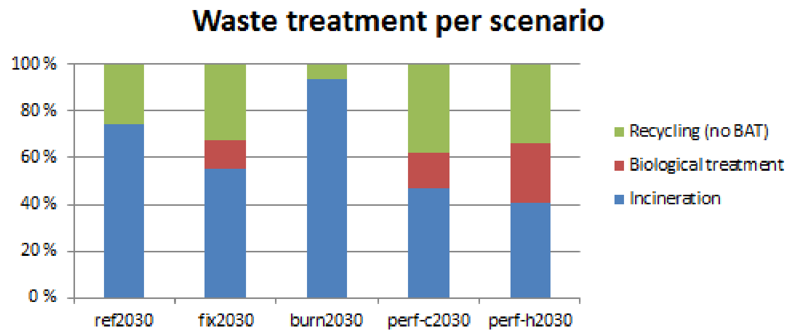

Figure 29: How waste is treated per scenario (2030)

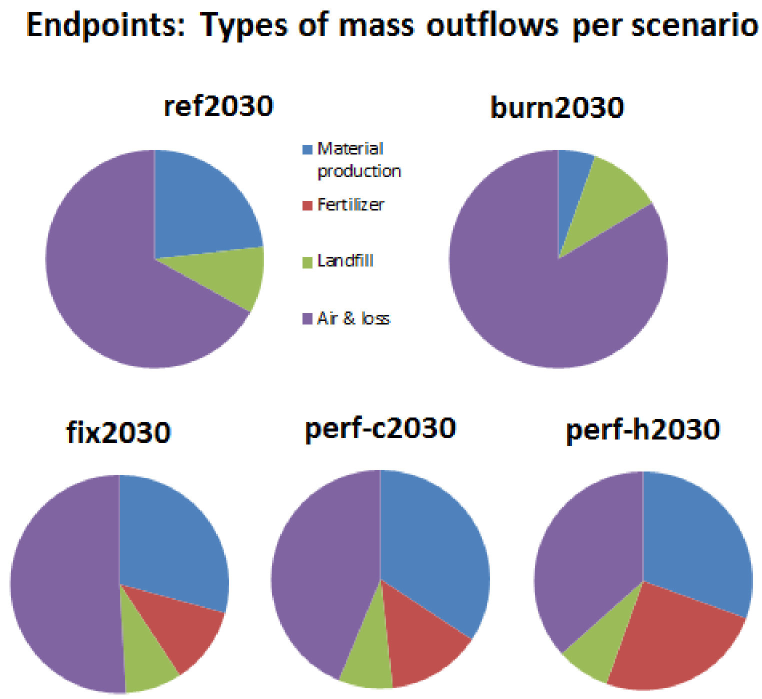

Figure 30: Flows of mass out of the system

was sent to incineration and 25.5% was sent for recycling.

After treatment, the mass eventually leave the system in one of four defined flows or states. Figure 30 shows for each scenario how waste is either turned into raw materials for material production (flows to processes 14 and 15), bio-residual for fertilizer production (to 13), emissions to air during incineration (a8-0), or sent for final deposition at a landfill. For ref2030 we see that as much as two thirds of waste generated exits the system in the form of air emissions. It is not purely a lossy process, as it produces heat at the same time. Short of a quarter/fourth went for material production and roughly 10% went to the landfill. As the scenario with the second-to-most amount of waste sent to incineration, this is reflected overall in the results: second-to-most sent for incineration and mass outflow to air.

Energy efficiency for each scenario is presented in figure 31. ref2030 has the second to highest efficiency, after the burn scenario.

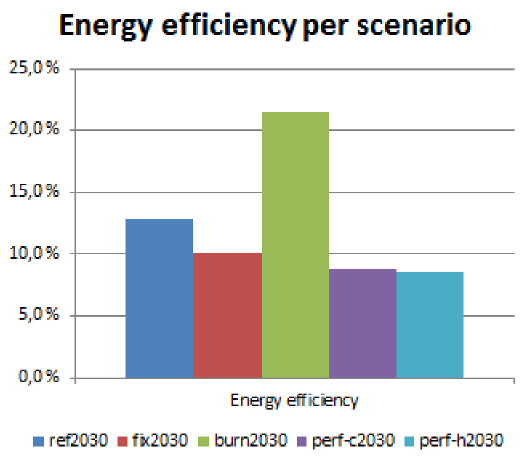

Figure 31: Energy efficiency per 2030 scenario

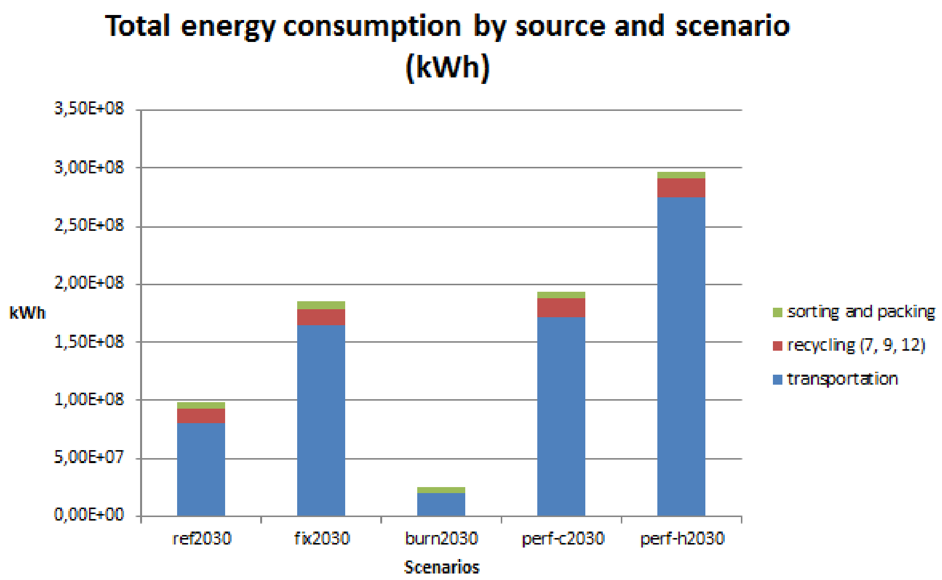

Figure 32: Energy consumption to transport, process recycling, other processes

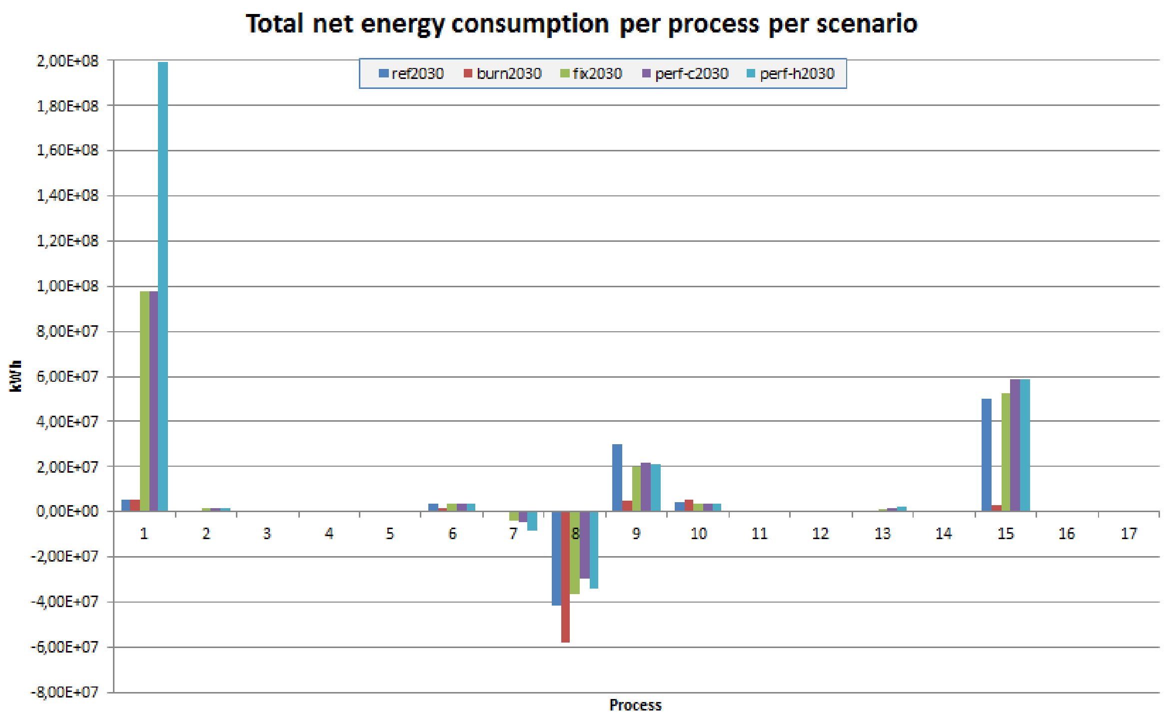

Figure 33: Total net energy consumption per process, all scenarios in 2030.

The total energy efficiency of the system as seen from figure/table 26 is just below 14%, which is the second highest of all scenarios. This is understood by the large share of waste sent to incineration, as shown previously in figure 29, which contributes to a high energy output. As for the feedstock, this number will be the same for all scenarios of a given year, except for a slight change in the central sorting scenarios as a result of diverting organic waste over to its organic fraction and for the perf-h also a change in the sampling analysis. The three other values of transport process and energy out varies widely among the scenarios. To understand the energy efficiency number, figures 32 and 33 display the energy consumption for types of processes and the exact processes, respectively, where energy consumption takes place. We see that for all scenarios in figure 32, including the reference scenario, the majority of the energy consumption takes place during transportation of waste, meaning the collection phase, and this is further underlined in 33. The second largest consumption takes place in recycling in process 15, material production. It must be noted that the data applied downstream is of high uncertainty, but most likely is are these numbers on the lower end of the actual numbers.

5.1.2 Fix scenario

The measures implemented in fix2030 will give quite starkly different results compared to the ref2030, and the chief point here is the implementation of organic separation and central sorting. Comparing these two would be an attempt to see how population growth and waste generation will impact the waste management of Trondheim municipal waste in 2030. In table 25 fix2030 attains quite a high MRR of 42.0%. The Trondheim rate is significantly lower at 38.4% as opposed to the reference scenario, where the Trondheim rate was higher than the MRR. For all the central sorting scenarios the case is that a

fix2030

MATERIAL INDICATORS

Material	Collection	Sorting	Recycling	Trondheim
glass	73,5 %	73,7 %	66,2 %	73,8 %
metal	24,4 %	92,4 %	86,0 %	26,3 %
plastics	29,5 %	42,4 %	33,2 %	13,5 %
organic	44,4 %	36,4 %	40,0 %	36,4 %
pap. & card.	76,7 %	83,4 %	78,6 %	77,3 %
residual	0,0 %	0,0 %	0,0 %	4,5 %
hazardous	0,0 %	0,0 %	0,0 %	0,3 %
textiles	0,0 %	0,0 %	0,0 %	0,1 %
Aggregated	54,0 %	43,8 %	42,0 %	38,4 %

ENERGY INDICATORS

Energy (kwh)	
Feedstock	2,74E+08
Transport	1,65E+08
Process	2,06E+07
Energy out	4,67E+07
Efficiency	10 %

Figure 34: Performance indicators for fix2030

lot of material recovered at the central sorting facility is recovered from the residual waste and the Trondheim rate only cares about what is actually sent in its correct waste categories. So for these scenarios the case is that with the Trondheim rate is lower than the actual recycling. The clearest proof of this is the very large increase in efficiency from collection to sorting in the metal fraction. In fact, all fractions except for organics see an improvement in sorting efficiency except for organic waste, where there is loss through the central sorting facility.

Comparing the performance of fix2030 to the other scenarios in figure 28, fix does better than the incineration-based scenarios, but worse overall than the two perfect scenarios. The difference lies in the plastics, organics and P&C fractions.

The treatment figure 29 shows that more than 60% of waste material is sent for recycling and biological treatment, which is more than in the ref2030 scenario. Comparing the outflows to ref2030 in figure 30, we see the same pattern. More than 60% of outflows goes to some kind of material production, and as a consequence of less mass sent for incineration, both emissions to air and deposition at landfill has been decreased compared to ref2030.

Compared to ref2030, fix2030 loses energy in every area. The transportation work is more intensive with more downstream chains due to one more collected category, more material is processed, which also leads to more transportation work, and the energy out is lower because of less heat production at the incineration plant which is not made up for by biofuel production. So, amongst all the 2030 scenarios energy-wise the fix-scenario is on top in consumption with surpassing 1,89 10^8 kWh , as seen in figure 32, but even so, the energy efficiency is the best of the three central sorting scenarios. Figure 33 reveals the cause; fix2030 consumes the least energy in processes 9 and 15, second to most in 1, but produces the most energy of all central sorting scenarios in process 8, incineration.

perf-c2030

MATERIAL INDICATORS

Material	Collection	Sorting	Recycling	Trondheim
glass	73,5 %	73,7 %	66,2 %	73,9 %
metal	24,4 %	92,5 %	86,0 %	26,4 %
plastics	29,5 %	70,4 %	55,3 %	21,9 %
organic	44,4 %	44,4 %	48,8 %	44,4 %
pap. & card.	76,7 %	98,8 %	92,8 %	77,8 %
residual	0,0 %	0,0 %	0,0 %	5,1 %
hazardous	0,0 %	0,0 %	0,0 %	0,3 %
textiles	0,0 %	0,0 %	0,0 %	0,1 %
Aggregated	54,0 %	53,5 %	50,9 %	42,2 %

ENERGY INDICATORS

Energy (kwh)	
Feedstock	2,74E+08
Transport	1,72E+08
Process	2,23E+07
Energy out	4,02E+07
Efficiency	8,6 %

Figure 35: Performance indicators for perf-c 2030

5.1.3 Perfect central sorting scenario

For the perfect central sorting scenario, it is identical to the fix2030 except for the changed TCs for process 2, the central sorting facility. This will impact the sorting efficiency directly and give repercussions for the recycling efficiency rate. The MRR of perf-c2030 is 49.8%, see figure 35. The other indicators follow the pattern we have seen in fix2030, with a drop in efficiencies downstream from collection to recycling, with Trondheim rate at the bottom due to not reporting downstream gains. Still, all efficiencies except for the collection rate are improved compared to fix2030, which makes sense as the scenario is based on the fix parameters except for the central sorting, which takes place in the system just before the point where sorting efficiency is calculated. Notably the drop between material recycling and Trondheim rate is most prevalent in perfc-2030 among all 2030 scenarios, this will be discussed further later. Considering all fractions as with fix there is a high gain in all fractions from collection to sorting efficiency, but also the improved central sorting facility leads to little to no loss in organic waste sorting. This scenario obtains the same results as the fix scenario for a lot of the fractions, differences lie in the carbon-based fractions: plastics, organics and paper and cardboard. which are all higher for both their sorting and their recycling efficiencies.

The perf-c2030 excels at plastics (55%) and paper and cardboard (88%) recycling, where it gains the highest MRR of all 2030 scenarios (figure 28.

The waste is treated in a manner similar to fix, with more sent for biological treatment and recycling, ending up in a non-incinerated part of less than 50% (figure 29). More is sent for material recycling, but the share going for biological treatment is not that larger compared to fix2030, some 8% percentage points.

Perfc2030 has the second to lowest energy efficiency and the second to highest total consumption of energy. As for per process, it has the most efficient waste collection of all organic-collecting scenarios, but at the same time, it gives the lowest heat output in the incineration plant, and the highest energy consumption related to downstream transport for material production (figure 33).

perf-h2030

MATERIAL INDICATORS

Material	Collection	Sorting	Recycling	Trondheim
glass	75,9 %	76,0 %	68,3 %	76,2 %
metal	29,9 %	92,9 %	86,6 %	31,6 %
plastics	52,6 %	42,4 %	33,2 %	23,2 %
organic	95,9 %	78,6 %	86,5 %	78,6 %
pap. & card.	87,5 %	88,1 %	83,4 %	87,7 %
residual	0,0 %	0,0 %	0,0 %	4,0 %
hazardous	0,0 %	0,0 %	0,0 %	0,3 %
textiles	0,0 %	0,0 %	0,0 %	0,1 %
Aggregated	82,6 %	58,7 %	58,3 %	55,8 %

ENERGY INDICATORS

Energy (kwh)	
Feedstock	2,74E+08
Transport	2,76E+08
Process	2,12E+07
Energy out	4,92E+07
Efficiency	8,6 %

Figure 36: Performance indicators for perf-h2030

5.1.4 Perfect households scenario

Recapping, perfh2030 runs fix with an adjustment to the sampling analysis simulating households getting better at separating their waste. This produces the highest KPIs yet for all four of them, with a MRR at close to 60%, 58.3% (figure 36). The potential is all the way up at a collection efficiency of 82.6%, which then sees some loss and drops to 58.7% sorting efficiency. The Trondheim rate continues to be the lowest rate of the four KPIs, but the drop is lower than for the two other fix-based scenarios. Looking at the in-between KPI-losses, less plastics are recycled, but it is gained by more organics recycled.

As per the scenario description for perfh plastic was moved from the residual waste category to plastics for the household sampling analysis. Due to imperfections in the method the distribution over the categories is a little bit different than for the two other fix scenarios, giving 1% more generated plastic, but the sum in tonnes is the same for all five 2030 scenarios.

If we compare the MRR per fraction to the other scenarios (figure 28), perfh scores highest for all fractions except for plastics and organics, as described for the perfc2030 scenario. Especially organic has a massively greater MRR at above 85%, which means high utilization of the resource.

Almost only 40% of the waste is sent for incineration, with over 20% going to biological treatment - this is almost all of the organic waste. Keep in mind that over 25% of all generated household waste in this model is organic waste, see figure 37.

Perfh2030 consumes more process and transport energy than fix2030, and produces more energy out, but in total, compared to the potential in the feedstock, the energy efficiency here is the lowest of all 2030 scenarios.

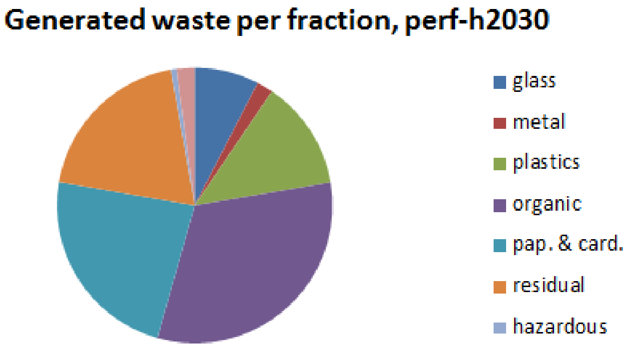

Figure 37: Generated waste per fraction, perfh2030

burn2030

MATERIAL INDICATORS

Material	Collection	Sorting	Recycling	Trondheim
glass	73,6 %	73,6 %	66,3 %	73,6 %
metal	24,6 %	24,6 %	23,4 %	24,6 %
plastics	29,7 %	0,0 %	0,0 %	0,0 %
organic	0,0 %	0,0 %	0,0 %	0,0 %
pap. & card.	76,8 %	0,0 %	0,0 %	0,0 %
residual	0,0 %	0,0 %	0,0 %	1,2 %
hazardous	0,0 %	0,0 %	0,0 %	0,0 %
textiles	0,0 %	0,0 %	0,0 %	0,0 %
Aggregated	35,5 %	6,1 %	5,5 %	6,3 %

ENERGY INDICATORS

Energy (kwh)	
Feedstock	2,72E+08
Transport	1,93E+07
Process	6,52E+06
Energy out	6,42E+07
Efficiency	21,6 %

Figure 38: Performance indicators for burn2030

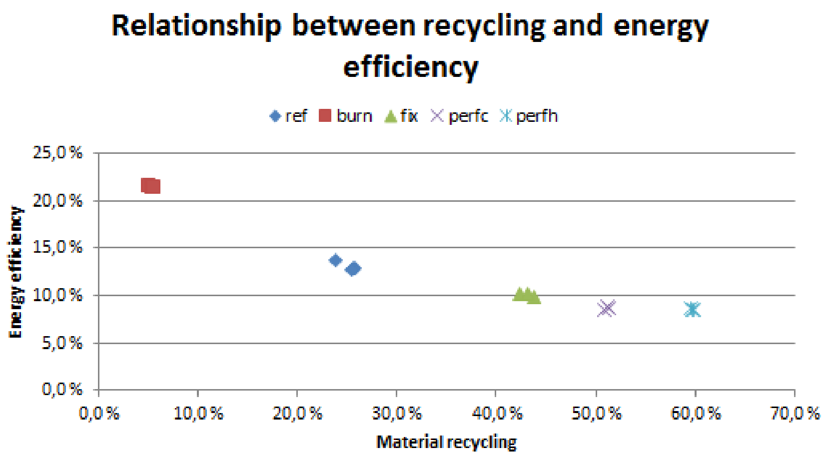

Figure 39: Relationship between material recycling and energy efficiency

5.1.5 Burn scenario

The highest loss of material from collection to sorting takes place where incineration is a major treatment form i. e. the reference and burn scenarios. Figure 38 reveals than in general the loss from sorting to material recycling is much lower than the collection to sorting efficiency loss, with the exception of the fix scenario. Sporting the highest energy efficiency, burn2030 also has the lowest transport and process energy consumption, and the highest energy production of all 2030 scenarios (figure 38). This is apparent in figure 33.

5.2 Overall results

Table 10: The best and the worst of the 2030 scenarios

EFFICIENCY:	collection	sorting	recycling	Trondheim	energy
BEST	perf-h	perf-h	perf-h	perf-h	burn
WORST	burn/ref	burn	burn	burn	perf-h

Figure 39 shows the relationship between recycling and energy efficiency. As less material is sent for incineration, less heat is produced and more energy is consumed downstream handling the waste. Figure 40 showing the correlation between incineration and energy efficiency looks to be the inverse of figure 39 with increasing energy efficiency the more waste is incinerated, which makes sense as incineration in this model is kind of the opposite of recycling when it comes to energy.

5.2.0.1 Development over time - the effect of changing waste generation

As a consequence of the way the models were designed, the results of reference scenario in the three other years look very similar to the first one. This can be seen in figure 41. The main development is that of a decrease in the material performance indicators and

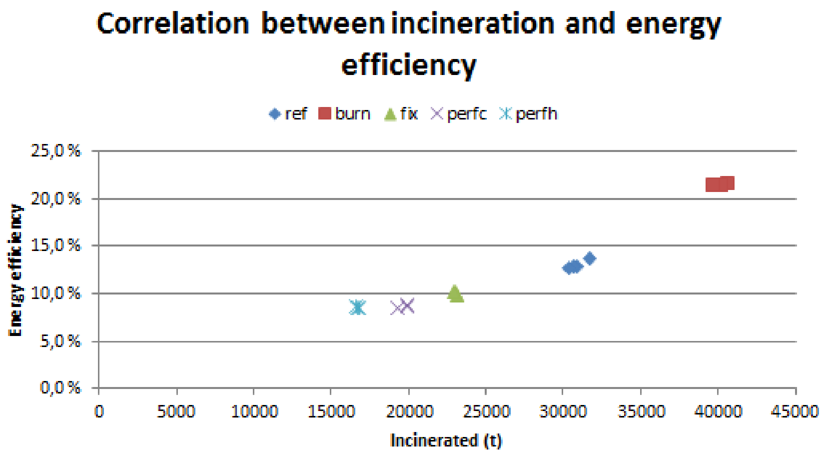

Figure 40: Relationship between incineration and energy efficiency

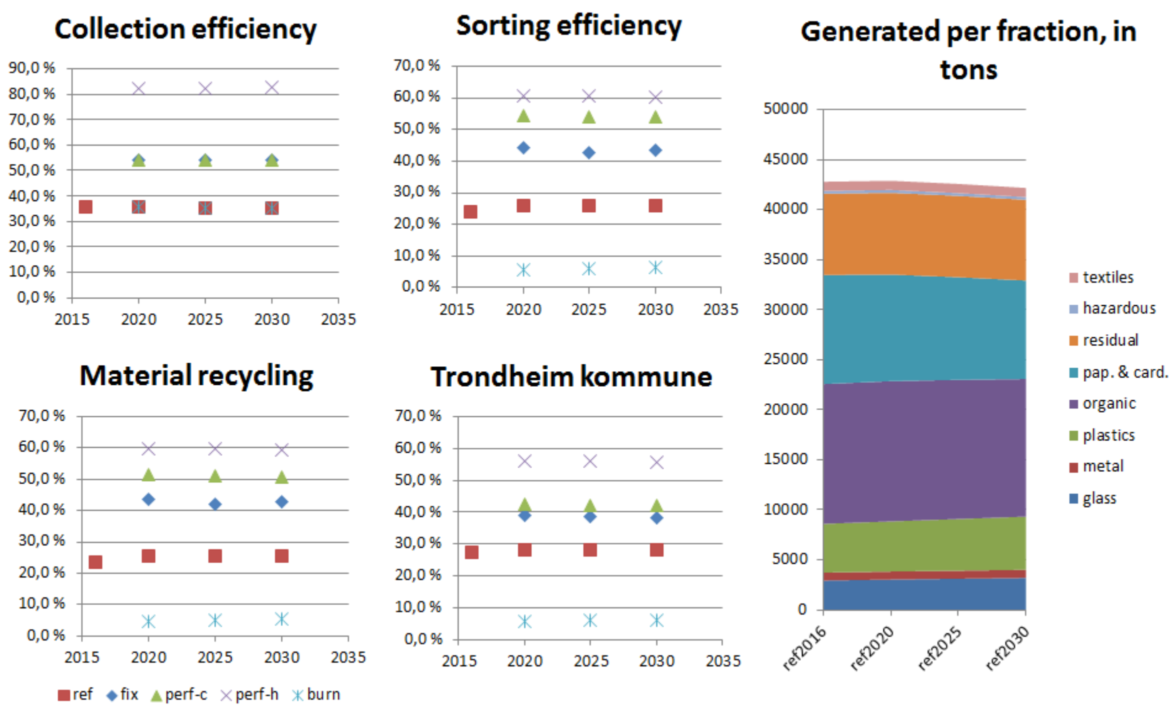

Figure 41: The development of indicators and waste generated over time

Sensitivity analysis - ref2016

		Material indicators						Energy indicators					
TC	Fraction	Col_fr	Col_tot	Sort_fr	Sort_fr	Recyc_fr	Recyc_tot	Energy ef	Transport	Process	Generate	Incinerati	AD
T16	plastics	0,00 %	0,00 %	100,00 %	6,75 %	100,00 %	5,70 %	-32,17 %	12,00 %	1,97 %	-29,71 %	-29,71 %	0,00 %
T27	organic	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %
T98	ap. & car	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %
T98	plastics	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	1,20 %	0,92 %	0,37 %	1,40 %	1,40 %	0,00 %
T98	metal	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	1,47 %	0,34 %	0,13 %	1,55 %	1,55 %	0,00 %

Sensitivity analysis - fix2020

		Material indicators						Energy indicators					
TC	Fraction	Col_fr	Col_tot	Sort_fr	Sort_fr	Recyc_fr	Recyc_tot	Energy ef	Transport	Process	Generate	Incinerati	AD
T16	plastics	0,0 %	0,0 %	0,9 %	0,1 %	0,0 %	0,0 %	0,3 %	0,0 %	0,2 %	0,3 %	0,4 %	0,0 %
T27	organic	0,0 %	0,0 %	100,0 %	26,2 %	100,0 %	29,9 %	9,4 %	1,2 %	1,2 %	9,9 %	-1,1 %	100,0 %
T29	plastics	0,0 %	0,0 %	97,6 %	11,0 %	100,0 %	9,2 %	-26,6 %	3,2 %	6,6 %	-25,1 %	-28,2 %	0,0 %
T98	ap. & car	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %	1,4 %	0,4 %	0,3 %	1,6 %	1,8 %	0,0 %
T98	plastics	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %	4,4 %	0,2 %	0,3 %	4,4 %	5,0 %	0,0 %

Figure 42: The results of the sensitvity analysis

an increase in the energy efficiency as the waste flowing through the system decreases. The noteworthy change is that all other things being equal, the change in waste input or generated waste leads to a change in the performance indicators. For a linear model, one would expect no such change as the relations between all parameters stay the same. As such, the change, which also seems to be different depending on the size of the generated waste means that the model is a non-linear model.

5.3 Sensitivity analysis

Table: The results of the sensitivity analysis

6 Discussion

6.1 Main findings

6.1.1 KPIs

Now, the key performance indicators will be used to assess and compare the system performance. All four of assess the system's success at collecting, sorting and finally recycling the material generated in households. The collection efficiency illustrates how successful the system is at collecting the correct waste fractions in the correct bins. Its improvement in the fix-based scenarios compared to ref-based scenarios is due to the collection of organic material, and for perf-h the vastly improved household rates play a large role. To improve the collection efficiency it seems then that collecting organic waste and getting households to sort better are efficient measures. The collection efficiency is unsurprisingly the same for ref2030 and burn2030, with them being essentially the same model at this system boundary.

For the sorting efficiency total values, there are losses in all 18 scenarios run. As there naturally are losses in sorting processes where impurities and missorting are taken care of, this is not surprising. What could be somewhat surprising is that there are gains for most fractions in all fix-based scenarios. This can be seen in the scenarios tables in figures 34, 35 and 36 and are evidence of the central sorting facility at work, separating out desired materials from the residual waste. Most of what is recovered are metals and plastic. For these fractions a central sorting facility is a band-aid on the wound that is inefficient household sorting. The largest gains are seen for the metal fraction, which is taken from a collection efficiency of 24-25% to above 92% sorting efficiency rate. Plastics are a mixed bag: the introduction and improvement of central sorting raises the sorting efficiency for fix2030 and perfc2030 by 12.9% and a massive 40.7% respectively, while the perfh2030 sees a drop in sorting efficiency compared to fix2030, even if the collection efficiency, due to improved household sorting, is very much more improved.

Examining the results closer reveals that the reason is that the quantity plastics collected in the plastics bin for perfh2030 is higher than the total plastics sorted out. This means that simply shifting the plastic from residual waste to plastic bin does not do much for the total recovery as long as there is central sorting involved. Household sorting efficiency and collection efficiency is not the most important factor for plastics and quite possibly could the collection technology system be simplified.

Continuing the fraction analysis, the fraction paper and cardboard, which already enjoys a high sorting rate, sneaks up above a 82% sorting rate in the fix-based scenarios. Combine it with with households gains 6 more percentage points, but also for paper the central sorting reign supreme, squeezing the last cellulose out of the residual waste. Overall, it is the loss of the organic fraction during process 2 (central sorting) which is decreasing the sorting the sorting efficiency compared to the collection efficiency in the fix scenarios, with the exception of perfect central sorting, which manages zero loss.

Overall, improving the sorting efficiency of a fraction seems to depend on how prevalent they are in the residual waste bin, i. e. how much loss there is in household sorting: For plastics and paper/cardboard the utilization and efficiency of the sorting facility is absolute key and has the most effect, meanwhile for organic waste household sorting efficiency is what decides the potential. For fractions not passing through the central sorting facility, it depends on their separate sorting facility losses, but since they are low in this model, the household sorting has the highest impact, as seen for metals in perfh2030.

The reason why assessing the sorting efficiency so closely is important is because it forms the potential of the material recycling rate. Downstream recycling rates can hardly be changed, but sorting efficiency is exactly what the municipality of Trondheim hopes to improve with the construction of a central sorting efficiency. From figure 25 each measure introduced seems to improved the overall material efficiency, but the results for perfh2030 improving household sorting efficiency having a larger effect (MRR of 49.8%) than improving the central sorting facility (MRR of 59.5%). Perfh2030 also seems to sport the lowest loss from sorting efficiency to material efficiency (0.6%), surprisingly alongside burn2030. Burn2030 probably has this low loss because the only fractions going to recycling is glass and metals, which are low-loss fractions. What keeps up the perfh2030 MRR is the seemingly strange increase from sorting efficiency to recycling rate in organics, which does not really make sense. The same increase are also found for perfc2030 and fix2030, meaning something is happening downstream of the central sorting facility.

For plastics it seems that the higher the sorting efficiency, the higher the percentage point drop to recycling rate. The highest loss is in the glass fraction, and lowest for the metals. For all scenarios the paper and cardboard loss of 4-5% very likely is what drags down the recycling rate the most, but all fractions see some loss. One has to remember that these indicators are based on weight, and that a loss in paper and cardboard is more important than for fraction constituting lower share of total weight, such as metal, glass and plastics.

For improving material efficiency, then, what seems to be most effective depends on the fraction considered. In figure 28 we see that for fractions glass, metal and organic waste, household sorting efficiency gives the highest MRR, but only for organic waste is there really any change of significance compared to the fix scenario. For plastics, and paper and cardboard, an improved central sorting efficiency gives the best results.

The Trondheim rate, or company specific material efficiency has consistently kept below in all scenarios except for the reference-based scenarios, where it just overtook the MRR. This has to be related to the fact that the Trondheim rate does not consider losses after sending off the waste for recycling (for plastics), or sorting (P&C and G&M). Thus, loss in recycling in ref-based scenarios are not taking into account, but neither are gains from central sorting in the fix-based scenarios. Also, the rate considers whole categories, and not the pure waste fractions, making it not really a number to compare to the three first KPIs.

As already described in the results, the energy efficiency (figure 31 directly relates to how much waste goes to incineration and how much goes to energy-consuming recycling processes and transport. There it is no surprise that the order of highest to lowest energy efficiency is the inverse of the highest to lowest MRR. Perfc2030 and fix2030 have different transport energy consumptions, despite the same energy layer defined, due to exactly this relation: perfc2030 recovers more material and have therefore slightly more downstream consumption of energy. Loss early on, sent for incineration, leads to a higher energy efficiency. As seen in figure 39 the relation between the recycling rate and energy efficiency seems to be exponential and the relation seem to have a lower limit, even if the material efficiency increase by 10%s of percentage points. The part of the energy efficiency equation directly modifiable by the municipality relates directly to how the collection system is designed, and indirectly to the purity of the waste collected.

7 Conclusion

The results of the model shows that the material recycling rate in the reference scenario of 2016 was found to be 23.8%, and that the implementation of measures as modelled in the fix scenario could increase it to 42% in 2030. The highest MRR found overall was 60.0% for the perfect households scenario in 2020 , while the scenario with the best MRR in 2030 was also the perfect households scenario, with an MRR of 59.5%. As for the energy use in the system a high rate of recycling seems to cause a high consumption of energy. The energy efficiency was the highest at 21.6% in the burn scenarios, other than that the reference scenario did the best here.

The most critical factor for deciding the material efficiency seems to be the collection of organic waste. Next on the list is the central sorting, which recovers more of the paper and cardboard - the other large recyclable fraction - and plastics - which is a under-recycled fraction. In general for fractions prevalent in residual waste central sorting is the most important measure to recover them. For fractions collected by themselves or which are hard to separate in such a facility, household sorting is key. The energy layer seems to be very simple in that the higher waste input to the incineration and the lower for recycling, the more energy is produced in the incineration plant and t he less energy is consumed downstream.

The municipality's own target of 50% is met by both perfect scenarios, for all years. The fix scenario does not manage more than 45.6%, in 2020. Taken at face value, the only EU target which was met was the perfect households scenario in 2020. In 2030 it falls short with just 0.5%, meaning there is a potential here. Fortunately the real rate is higher, due to waste quantities not included in the model, and the meaning of material recycling as defined by the EU. How much higher is uncertain at this time, but to reach the newest EU targets for 2030 the fix scenario needs to be 27% points higher. A combination of better households and better central sorting facility technology could be imagined to only need around a positive 15% from adjustment to the real material recovery rate. For the municipality of Trondheim this means that their intended measures are a good start, but further focus on education of the public is needed while technological improvements might take the blunt of the work in a central sorting facility.

The model itself builds on a series of assumptions where there is a lot of uncertainty for some parameters. There is a potential for the model to be improved in this aspect. The final results should therefore not be taken as facts, but as indicators. Still, as the target was to look into the future, and not simply gain as a precise description of the current situation as possible, with precaution such results from such a model plays a role in planning for sustainable waste management.

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