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Material flow analysis, carbon footprint and economic assessment of alternative collection and treatment of domestic household waste from the region of Funen, Denmark

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Material flow analysis, carbon footprint and economic assessment of alternative collection and treatment of domestic household waste from the region of Funen, Denmark

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Executive summary

The structure and objectives of the study

This work adressed the current and potential (future) efficiency of domestic household waste management in the region of Funen, in terms of material recovery, carbon footprint and economic costs. This report was structured in three parts consisting of:

- Part 1 contains a comprehensive mapping and characterization of the existing (2013) waste management system in the region of Funen, including waste collection schemes, waste flows and treatment facilities;
- Part 2 documents the methods used and the results following (1) mass flow modelling of the current and alternative waste management systems designed for the region, and (2) carbon footprint assessment of the modelled systems;
- Part 3 documents the methods and results following a budget-based economic analysis of systems.

The main objective was to assess current practice and to explore potential avenues/strategies which would lead to (1) higher separate collection and recycling rates, and (2) potential climate change savings, while also evaluating the potential costs of new initiatives. A specific focus of this work was to go beyond today's background framework conditions and include an assessment of the significance of the changes in backgroung conditions, such as overall Danish policy, strategies and ambitions for future renewable energy integration and climate change mitigation. This implied a modelling of waste management in four background time perspectives: (1) the Present or 2012-2020, (2) Mid-term or 2020-2035, (3) Long-term or 2035-2050, and (4) Beyond 2050. Future energy marginals and prices have high levels of uncertainty, however they do reflect the most likely direction of societal development, as they represent consensus energy policy targets laid out by both the present and the two former Danish governments.

The modelled waste management systems consisted of 6 main systems each with 4 variants, for a total of 24 main system designs. These are known as foreground systems. The 6 systems represent the current (2013) system in the region and five alternative systems, which reflect possible changes in separate collection such as the introduction of biowaste and commingled recyclables (dual-stream) collection. The 4 variants of each system are connected to the treatment of remaining residual waste, which was incineration or central sorting (three variations of central sorting).

Table 01: Matrix of systems modelled in the assessment; SF= single-family, MF = multi-family

Systems archetypes	Separate collection	Treatment of remaining residual waste			
		WtE: Incineration CHP	*CS-ADwet: Central sorting with wet digestion*	*CS-ADdry: Central sorting with dry digestion*	*CS-Biodry: Central sorting with biodrying*
System 0	Existing schemes	0-WtE	0-CS-ADwet	0-CS-ADdry	0-CS-Biodry
System 1	Existing schemes + Biowaste SF	1-WtE	1-CS-ADwet	1-CS-ADdry	1-CS-Biodry
System 2	Existing schemes + Biowaste SF and MF	2-WtE	2-CS-ADwet	2-CS-ADdry	2-CS-Biodry
System 3	Dual-stream	3-WtE	3-CS-ADwet	3-CS-ADdry	3-CS-Biodry
System 4	Dual-stream + Biowaste SF	4-WtE	4-CS-ADwet	4-CS-ADdry	4-CS-Biodry
System 5	Dual-stream + Biowaste SF and MF	5-WtE	5-CS-ADwet	5-CS-ADdry	5-CS-Biodry

The carbon footprint assessment was based on the so-called consequential approach[1].This comprises the modelling of system expansion in those cases, where the choice of waste management approach influences adjoining systems. When changing waste management, waste flows are re-directed towards new applications, and this in turn leads to influences on the systems within both energy and agricultural sectors as well as parts of the waste management sectors itself. When, for example, biowaste is seperately collected, one scenario is to model it as co-digested with manure. The influence on the agricultural system in this case can be one of two options: either (1) it attracts more manure to be digested instead of direct spreading on soil (reference manure management), or (2) it replaces other carbon rich substrates for biogas production such as energy crops. Therefore co-digestion is credited with savings from either avoiding the reference manure management or with avoiding the whole production chain for an energy crop. Another example, diversion of waste from incineration plants towards recycling and/or biological treatment liberates incineration capacity, which can be offered on the waste market. Import of combustible waste, already happening in Denmark, implies avoiding the treatment of this waste in the exporting country, which typically is based on disposal operations (landfilling).

In the progression of the Danish energy system from now until beyond 2050, biomass plays a role in both electricity, heat and transport fuel production. On the marginal, this biomass is modelled as being imported. But the global biomass marginal is not necessarily as constant, but may well be dynamic/progressing as time goes and global biomass demand increases.

In the carbon footprint assessment two different perspectives have, thus, been modelled: (1) a progressive biomass marginal, that reflects an increasing demand for biomass over time and (2) a dirty biomass marginal, which reflects the use of biomass with a high carbon footprint in all four time perspectives.

Combined, all 24 foreground system scenarios are assessed against a large variety of background system combinations, resulting in a total of 896 different sets of carbon footprint results. This comprehensiveness was justified by the fact that the nature of the background system is known to be most decisive for the

[1] Based on consequential LCA rationale, only processes reacting to the changes implemented in the management system were included, i.e. processes reacting in both the foreground systems and background systems of energy and materials production. This implies modelling of so-called marginal supplies/ marginal data.

carbon footprint results and the comparison between alternative foreground systems. By including this many variants of background systems, the study is very robust to any questions and ‘aber dabei’s’. The nature of the results in this way becomes a ‘pattern’ characterizing the differences between compared alternatives under the most probable varying future background conditions, and it supports understanding the robustness of conclusions and the dependency on future developments in background systems.

In the economic analysis we took different costing perspectives regarding the utilization chain for biomethane and Refuse Derived Fuel (RDF), respectively. For the biomethane use, we modelled either (1) biomethane combustion with production and sale of heat and electricity, or (2) biomethane direct sale to the gas grid, and for the RDF, we modelled either (3) RDF utilization for CHP or (4) RDF utilization in a “heat only” boiler.

Waste management in the region of Funen

The geographical scope of the study covers all 10 municipalities in the region, with a total of 486,000 inhabitants. The 226,000 households in the region were devided based on type of residence into single-family (73 %) and respectively multi-family (27 %).

The current waste management aproaches in the region bear significant differences with regard to separate collection schemes. Small amounts of biowaste is collected in two municipalities (Kerteminde and Nyborg) and composted locally. Most common is kerbside collection of paper, cube collection of paper and glass and recycling centres which receive all of the focal recyclable material fractions. Residual waste is universally sent to incineration, with most of it being combusted in Odense and the remaining in Svendborg, while a small portion is transferred to Kolding, Jutland. Most sorting and quality checking of recyclable materials is performed locally, however no actual recycling operations take place in the region.

277,000 tonnes of municipal solid waste (MSW) was collected in the municipalities per year (2013). This includes garden waste, wood, small and large combustibles, plastics, metals, glass, cardboard, paper, food-waste and residual waste (the figure does not include hazardous waste and some bulky waste fractions). Of this total figure, some waste streams were not relevant for this study, mainly because their generation and management would not be affected by changing property close collection schemes. Therefore, after the subtraction of streams such as garden waste, wood, small and large combustible, the functional unit[2] of this study was defined as 157,007 tonnes of daily generated domestic household waste. Based on the defined functional unit, 694 kg of daily household waste is generated per household in the region of Funen per year (2013). This consists of 189 kg of recyclable material (paper, cardboard, glass, metals, plastics) and 11 kg of separately collected biowaste, while the remaining 494 kg is collected as residual waste.

Mass flow modelling results

The five simulated alternative systems were shown to potentially increase separate collection in the region from the current 29 % to 50 % with introduction of source separation of biowaste (covering all households), to 41 % with separate collection of recyclables in a kerbside dual-stream, and to 63 % with both biowaste and dual-stream separate collection.

[2] The functional unit is the management of 157,007 tonnes of waste, thus all material and energy flows, as well as system burdens and savings, are thus related to this quantity of waste.

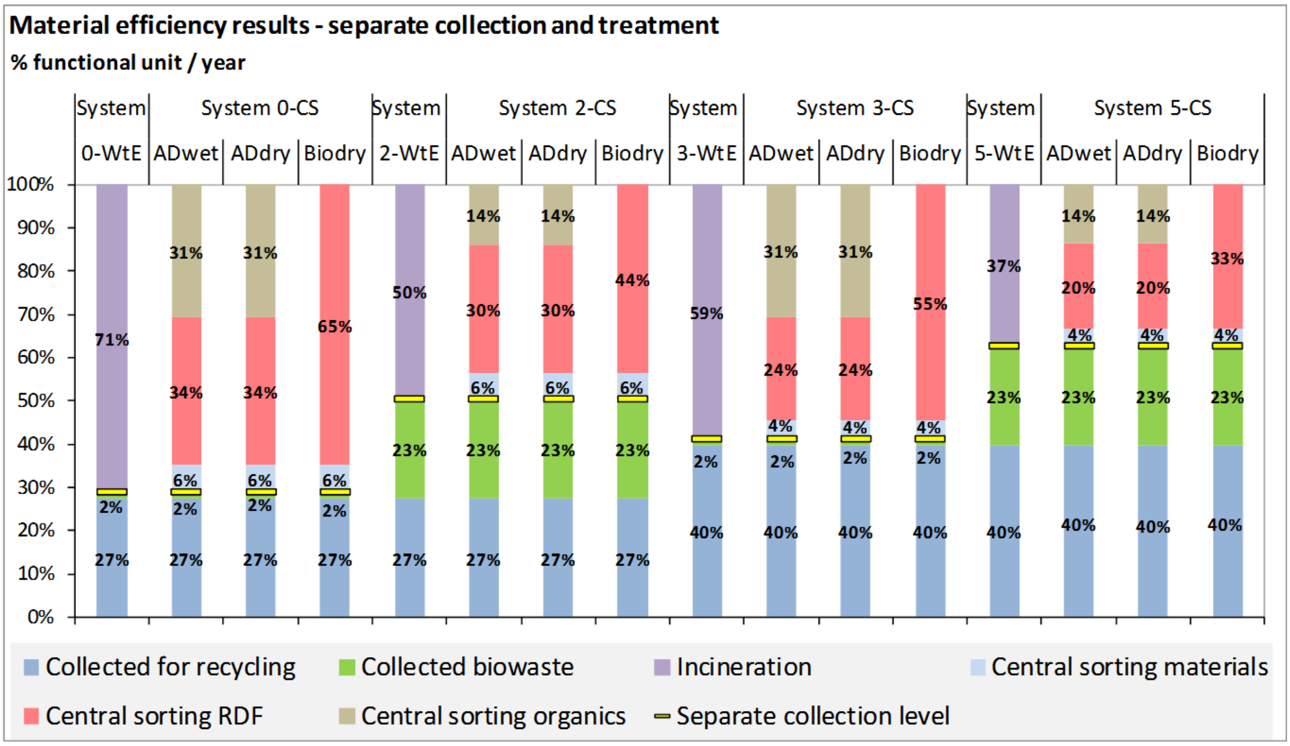


Figure 01: Summary of material efficiency results

Recovery of metals from incineration ash was shown to contribute an additional 1-2 % to material recovery in the region, while central sorting could contribute between 3 % and 5 %, with recovery of metals and plastics (depending of the source separation in the system).

Carbon footprint results

The overall results showed that the potential for climate change mitigation (GHG emission savings) associated with waste management in the region is substantial. Further, that the significance of background system development is very large, and that future waste management strategies, therefore, should consider the development towards 2050 of the background energy system in Denmark.

The change from residual waste incineration to central sorting (both with the current separate collection system and the alternative dual-stream), was shown beneficial from a global warming perspective in all four background time periods. This was due to a threefold contribution by central sorting to: (1) GHG savings by material recovery for recycling, (2) GHG savings by contributing to flexible power and heat production, and (3) GHG savings from combustion of imported combustible waste, due to liberated incineration capacity.

Biowaste separate collection was found to contribute to significant GHG savings compared to incineration of the organic fraction, especially when co-digested with manure. With regard to the two consequential perspectives, i.e. avoided reference manure management and avoided production of energy crops, the latter was found to have the largest GHG savings potential, due to avoided direct and indirect land use changes associated with the production of energy crops.

The combination of separate collection of biowaste and central sorting of remaining residual waste appeared to yield the largest GHG savings in the future time perspectives.

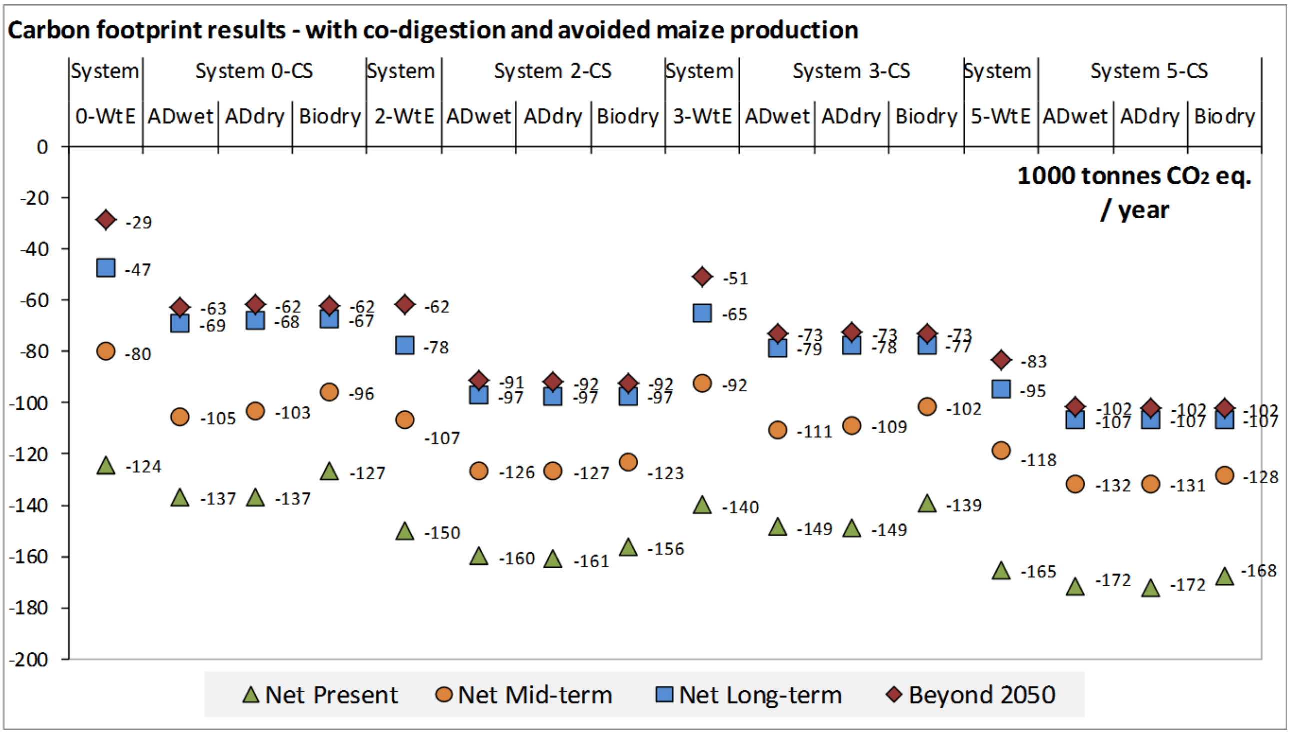


Figure 02: Summary of carbon footprint results

Budget-based economic analysis results

The analysis showed that an overwhelming large share of total system costs are due to waste collection, in all systems covering more than 50 %. The installation of biowaste and dual-stream collection in every household in the region was shown to lead to a near doubling of collection costs, however this could be subject to a more detailed investigation of options for optimization.

In general, two of the system variants with central sorting (with wet and dry digestion of organics) had higher net system costs compared to the variants with waste incineration in all four time perspectives, with one exception. This was in the Long-term perspective, when biomethane was assumed sold and replaced on the market synthetic gas produced from biomass (SNG). In other words, when/if the displaced methane marginal at some point becomes a SNG from biomass-based synthesis, the economy of converting biowaste into biogas will be significantly better than the other alternatives. The third system variant with central sorting (with biological drying) achieved similar results as waste incineration and in the costing alternative with RDF utilization in a district heating boiler, it showed potential for cost reduction compared to incineration.

Future price differences between continuous (base) and flexible (regulating) production of electricity and even heat (by storing RDF for winter use), have the potential to improve significantly the net system costs of especially system variants with central sorting, as they support the maximum possible system flexibility.

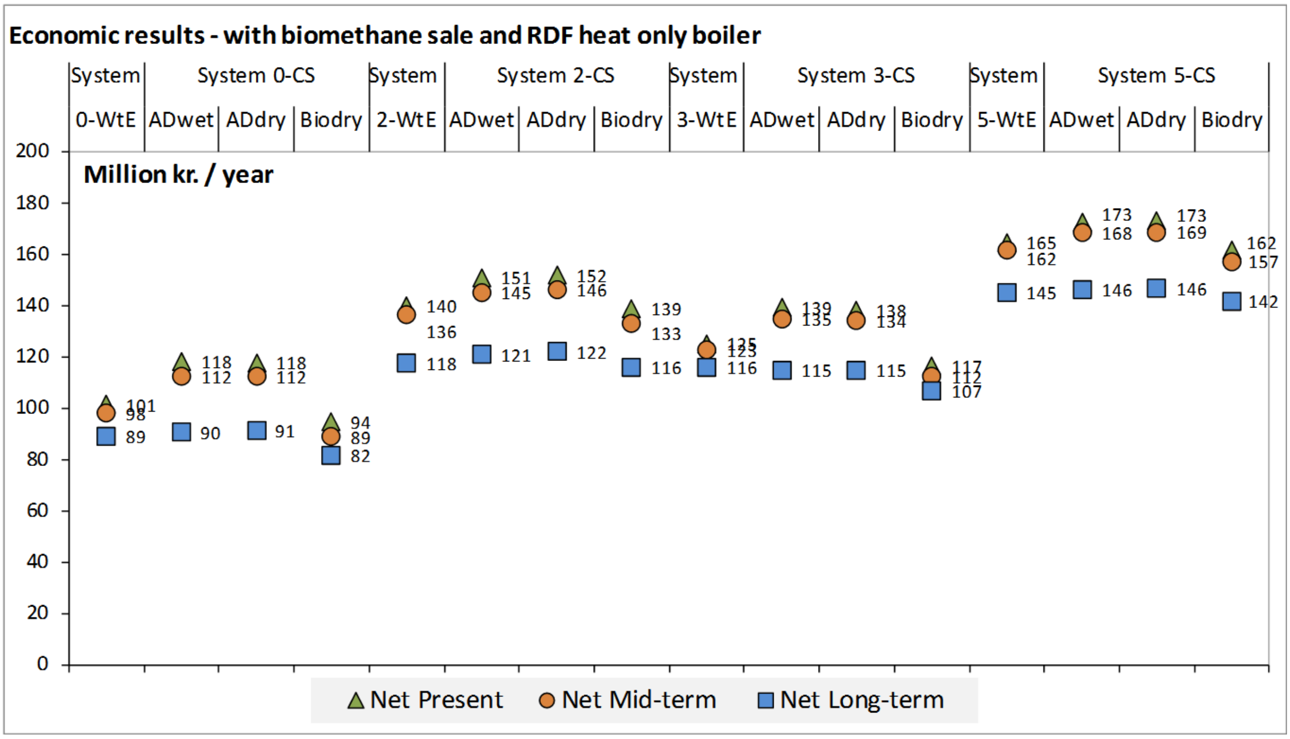


Figure 03: Summary of costs results, as net system costs in the costing perspective with biomethane sale and RDF use in a heat only boiler.

Table of Content

Three Appendixes are available (1) PFDs, (2) carbon footprint and (3) economic assessment

Introduction

This section will be used to introduce the motivation for the study, mostly referring to changes occurring in framework conditions which are affecting waste management in Denmark and experiences with different waste management approaches.

Framework conditions

"By 2020 the recycling of waste materials such as at least paper, metal, plastic and glass from households shall be increased to a minimum of overall 50 % by weight (European Comission, 2008)".

Such is the target defined by the European Union´s Waste Framework Directive 2008/98/EC Article 11 on Re-use and Recycling. This target should be achieved in all member states in order to move towards a European recycling society (European Comission, 2008). The member states (such as Denmark) should implement separate collection of at least paper, metal, plastic and glass. Article 22 of the Waste Framework Directive refers to biowaste (organic) collection and encourages member states to implement separate collection of biowaste with respect to compost or otherwise treat it in a way that "fulfils a high level of environmental protection" (European Comission, 2008).

The Danish Government has implemented this in a national resource strategy (The Danish Government, 2013), in which the targets are specified; a minimum of 50 % of the household waste material fractions (including organic waste, paper, cardboard, glass, wood, plastic and metal waste) should be recycled rather than incinerated by 2022. Based on this the Danish municipalities have to implement whatever collection scheme they find appropriate in order to reach these common goals.

Other framework conditions can be related to the Danish ambitions to be using 100 % renewable energy sources in 2050 (The Danish Government, 2011). The transition towards such an energy system comes with specific challenges, such as the integration of large shares of fluctuating renewable sources like wind and solar. For this reason, the energy system of the future will rely on capacity to store surplus energy in various ways and to produce electricity in a flexible manner from sources such as biomass. Waste incineration contributes in Denmark significantly today to energy production (i.e. 5% of electricity and 20% of heat) and therefore waste energy could play a significant role in the future. However, incineration has to run more or less continuously, which means that in the future it will sometimes compete with wind electricity. What is needed is to store the energy in waste and use it to replace other sources, i.e. biomass for electricity, when the wind is not blowing or fuels for transport.

Lastly, most Danish biogas plants are based on manure, and a lot of the plants seek to supplement this with other biological material to reach a higher dry matter content and thereby a higher biogas yield which will make the plants more economically profitable (Birkemose et al., 2013). The energy settlement from 2012 has the objective to increase biogas production through increased subsidies, which was intended to increase utilization of manure for biogas production to 50 % by 2020 (Energistyrelsen, 2014). Biowaste from separate collection can in this case be used as an alternative co-substrate in manure-biogas plants, potentially replacing other co-substrates such as energy crops, which entail significant environmental burdens.

Challenges of implementation in Denmark

Given by the resource strategy, Denmark must almost double the recycling rates from household waste from 22 % in 2011 to 50 % by 2022 (The Danish Government, 2013). This has been met with some critique. For one thing, the responsibility is given to the municipalities with not much guidance on how to approach this. This goes for questions as how to do it and with respect to quantity/quality requirements of the sorted fractions (Ingeniøren, 2013b). Another thing is the influence the resource strategy has on the waste incineration sector (waste-to-energy, WtE), since the supply of household waste to the WtE´s will be reduced by an estimated 25 %. Also the economic advisers have criticized the economic foundation of the transition from incineration towards recycling (Det Økonomiske Råd, 2014). Diversion of waste towards recycling will inevitably mean that less energy will in total be recovered from the remaining waste. Further diversion on biodegradable waste towards bio-gasification will limit waste remaining for direct waste incineration. The existing waste incineration infrastructure can however still play an important role. Freed incineration capacity can be used to treat waste imported from other European countries and this can induce substantial environmental benefits, if this waste would be otherwise landfilled.

Already a consequence of decreasing waste availability (financial crisis) has resulted in overcapacity at many incinerators around Denmark. In 2013 it was published that 10 out of 27 incinerators import waste from countries that lack capacity (Ingeniøren, 2013a). Benchmarking of the waste sector also emphasize this problem with overcapacity being filled by imported waste or biomass (Dansk Affaldsforening et al., 2013). One common attitude is that incineration is highly efficient in Denmark (recovery of both heat and electricity) and it is difficult to accept that we as a nation should phase out waste incinerators. Many of the plants are well maintained and thereby still have a long lifetime, and business will have to continue; whether it happens with Danish or foreign waste or even bio-fuels is an important question.

Waste management approaches

In Denmark public collection points (cube systems) and recycling centres have been well implemented and used for disposal of different recyclable material fractions. Kerbside collection of recyclables has been seen in some municipalities since 1980'ies, and in the last decade more municipalities have followed the idea.

Although the EU's waste legislation regarding MSW and packaging waste clearly mandates source separation as the main recovery path, it still allows for alternative schemes in which recyclable materials are sorted from residual MSW. Separate collection has been widely implemented throughout Europe, however, most successfully in non-urban areas. In urban areas, the participation (citizens' engagement) is often poor resulting in low source separation efficiency and higher contamination levels of separated waste streams (DAKOFA, 2014, Dahlén and Lagerkvist, 2010). Further, separate collection systems often lead to increased overall collection costs.

Recovery of recyclables from residual MSW at central sorting facilities contributes today significantly to the recycling rates of MSW and packaging waste in countries such as Spain, France and Greece. In Austria this approach is used to supplement separate collection in four large cities (for plastics), which display lower household source separation participation. Around 10% of municipalities in the Netherlands have chosen central sorting of residual MSW as the main route to recovery of plastic packaging. Pilot and full scale studies in the Netherlands and Germany have demonstrated that the quality of metals, plastics and beverage cartons is not substantially different if these materials are sorted at the households (and collected separated or commingled) or are centrally sorted by machines when collected mixed with residual waste(van Velzen et al., 2013b, van Velzen et al., 2013a). Furthermore, the differences in quality do not adversely affect the downstream recycling processes (Luijsterburg and Goossens, 2014). However, for plastics and beverage cartons, there is a difference in legal status, since these materials have been in contact with residual waste, with the consequence that they cannot be recycled back to food packaging (Lighart et al., 2013). In reality, this is not such a big issue because in countries with separate collection of household packaging waste, these materials are anyway not recycled back to food packaging, but more that often are downgraded to less demanding applications, such as flower pots, pipes, garbage bags or even sound barriers and outdoor furniture.

Regarding biodegradable waste, several technologies exist today which are applied in full scale or pilot scale, and which are able to extract biodegradable waste fractions from mixed waste into a biomass output intended for anaerobic digestion. For example, in Denmark, REnescience developed by DONG and Ecogi developed KomTek Miljø are promising techniques for such separation. Internationally, an extrusion press developed by the Dutch company db technologies BV and the Italian company VMpress s.r.l. is being used in full scale in several European countries for this purpose. Initial studies regarding the quality of the biomass recovered with these technologies suggest that it is similar to biomass recovered through separate collection programmes and subsequent pre-treatment. Nevertheless, because centrally recovered biomass has been in contact with residual waste, there is a higher risk for occasional occurrence/peaks in certain contamination (e.g. heavy metals, plastic additives), and therefore the options to manage digestion residues will most likely be more limited (i.e. application to soil) in comparison to source separated biowaste.

Danish municipalities are though hesitating when suggesting central sorting as an option. This is partly because the tendency is that they want to inform and educate the citizens to be responsible with regard to waste disposal, but it is also because they don't want to compromise on having a safe and healthy working environment for their employees. The challenge will therefor also be to create a fully automated sorting line that will not endanger the health of any employees.

Goal statement

The core of this project concerns waste management of household waste in the region of Funen, Denmark. In cooperation with the municipalities on Funen and taking an off-set in the newly proposed Danish "Resource strategy", the aim is to give a technical, environmental and economic evaluation of alternative ways of managing the waste treatment and material recovery while at the same time achieving the greatest synergy with the energy system of the future.

To achieve this, a number of alternative systems will be designed and modelled, and these systems will be compared from the perspectives of resource recovery efficiency, Global Warming Impact potential and total system costs/ benefits. The systems will comprise different degrees of and solutions to separate collection, automated central sorting, materials recovery for recycling, biowaste separation with different uses of the bio-fraction, and waste incineration for energy recovery.

The project will open the way for municipalities to make sound decisions regarding which strategies to take towards collection systems, increasing recycling rates, biowaste use and optimizing the use of waste-to-energy.

1 Part 1: Mass flow assessment of current MSW management in the region of Funen

Part 1 of this report documents the methods used and results obtained from the data collection regarding the establishment of the current/reference waste management system in the region of Funen. This includes a thorough description of the catchment area from demography to waste management approaches and material collection.

1.1 Methods - Data collection

In order to map in detail the baseline system of current management of household domestic waste in the municipalities on Funen (including all relevant actors), all the involved municipalities and renovation companies have been contacted to provide information.

The data collection was based on a questionnaire, which was meant to open the dialog with each of the parties involved. This was divided into different categories; (1) material quantities and collection schemes, (2) characteristics of mixed waste streams (e.g. residual waste), (3) transportation/collection parameters, (4) transfer stations/ municipally owned sorting facilities, (5) actors/end-stations for the materials, (6) costs related to point 4 and (7) future plans for the waste management system.

The questionnaire lead to interviews by mail, phone or personal meetings in order to get a proper understanding of the information as well as collecting missing data. Category 1, 3, 5 and 7 have been answered in details by all municipalities. None of the municipalities (except Odense as part of the characterization of average Danish household waste in (Petersen et al., 2014)) had any information on the composition of the mixed waste streams (2). Few municipalities had transfer stations or municipal owned sorting facilities whereby category 4 and 6 was difficult to comment on. Supplementary data related to costs of the waste management system has been collected subsequently.

Denmark's Statistics have been used in order to characterize the catchment area of Funen on other parameters like population and residential types.

1.2 Characterization of the region of Funen

The region of Funen (the main island of Funen incl. Langeland and Ærø) has served as the waste catchment area boundary. Funen has a geographically central position in Denmark, Figure 1, and the area consists of 10 (very different) municipalities.

This section will be used to describe demographical parameters of the catchment area and to give an overview of the waste management systems found in the 10 municipalities.

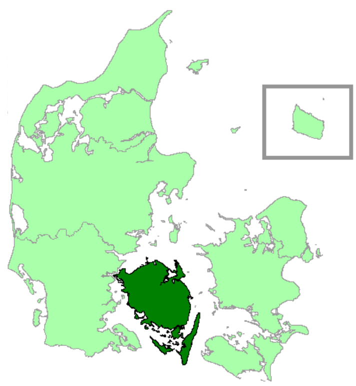


Figure 1: Location of the region of Funen (dark green), Denmark

1.2.1 Demography of the catchment area

The catchment area consists of 10 municipalities which overall account for 486,000 inhabitants and 226,000 primary households.

Figure 2 illustrates how the population is distributed between the municipalities on Funen (left) and the population densities within each municipality (right).

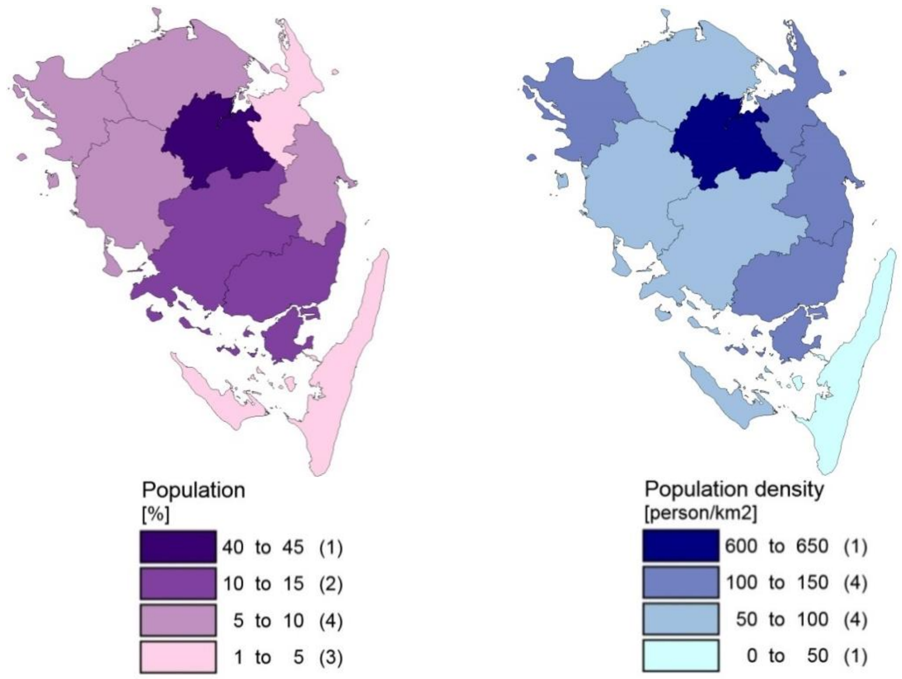


Figure 2: Illustrations showing distribution of population in % within the region of Funen (left) and population density in persons/km^2 in each of the 10 municipalities (right) (GIS info and Danmarks Statistik). The more intense the colour is, the larger the share/number.

The population is not equally distributed throughout the region; a concentration of inhabitants is found in Odense municipality. 40 % of the total population in the region resides in Odense municipality, and this is also the municipality with the largest papulation density (640 persons/km^2), which corresponds with Odense being the third largest city in Denmark. The average population density in the other 9 municipalities is around 100 persons / km^2. In the other end of the scale we have Langeland municipality, which has only a small share of the total population (2.6 %) and the lowest population density (44 persons/km^2). Faaborg-Midtfyns municipality accounts for a fairly large share of the population (10.5 %) but also the largest area, which leads to a relatively low population density.

According to Danmarks Statistik, rural areas *(landdistrikter)* are defined as areas with scattered buildings or coherent estate with less than 200 inhabitants. The ration between population in urban and in rural areas in each municipality has been illustrated in Figure 3. In Odense municipality only a small share of the population live in what has been defined as rural areas, which corresponds to the previous presented characteristics of dense population within the municipality. Langeland and Nordfyns municipality have the largest share of population living in rural areas (~40 %), whereas the most common share is around 25 %. As an average for all the municipalities the share of rural areas is 16 %, which is mainly due to the weight of the tendency in Odense municipality.

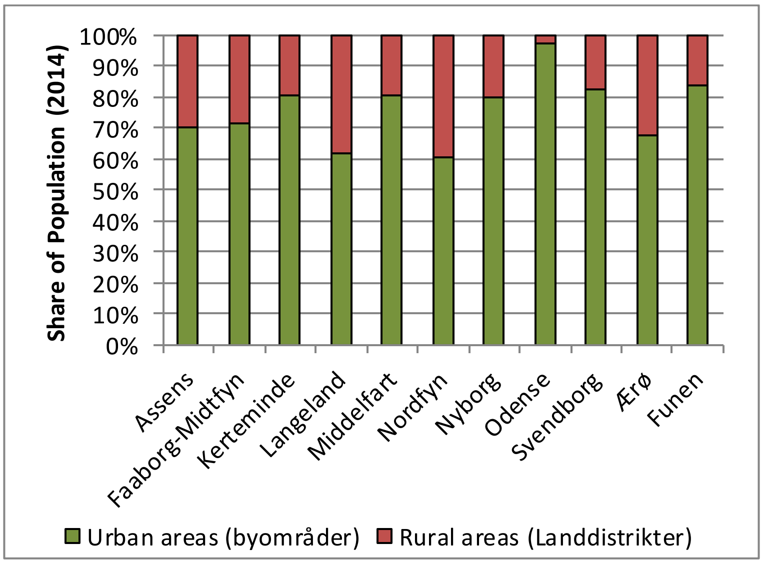


Figure 3: Ratio between population in urban and in rural areas in each of the 10 municipalities on Funen (according to Danmarks Statistik, 2014).

In terms of residential types the population can be distributed between single-family and multi-family households. Single-family households include villa and terrace housing, whereas multi-family households include apartment/storey buildings and residential halls *(kollegier)*. Single-family households are characterized by higher numbers of residents and thereby more residual waste generation per household (Petersen and Domela, 2003). Each household has its own bin and its own responsibility towards sorting etc. Multi-family households on the other hand are typically characterized by a lower number of residents and also less residual waste generation per household. This category of residents is though also expected to feel less responsibility towards discarding material in a proper manor (sorting scheme), because they have to share the bins with others. Dansk Affaldsforening has (based on a quantitative analysis (Dansk Affaldsforening, 2013)) made four "waste profiles" that differentiate between the levels of engagement towards proper waste management within the Danish population. People living in apartments tend to be more the "convenient"-profile or the "indifferent"-profile, which means that sorting waste for this type of population is not all about the greater good, but more about convenience and whether it takes too much of an effort to do so. Single-family households usually have more space to store material (recyclables) in order to bring them to the recycling centres, whereas multi-family households finds it less convenient to do so because of lack of space.

Figure 4 illustrates the share of single family (left) and multifamily (right) households in each of the 10 municipalities in the region of Funen. The two illustrations mirror each other since they together represent 100 % for each municipality.

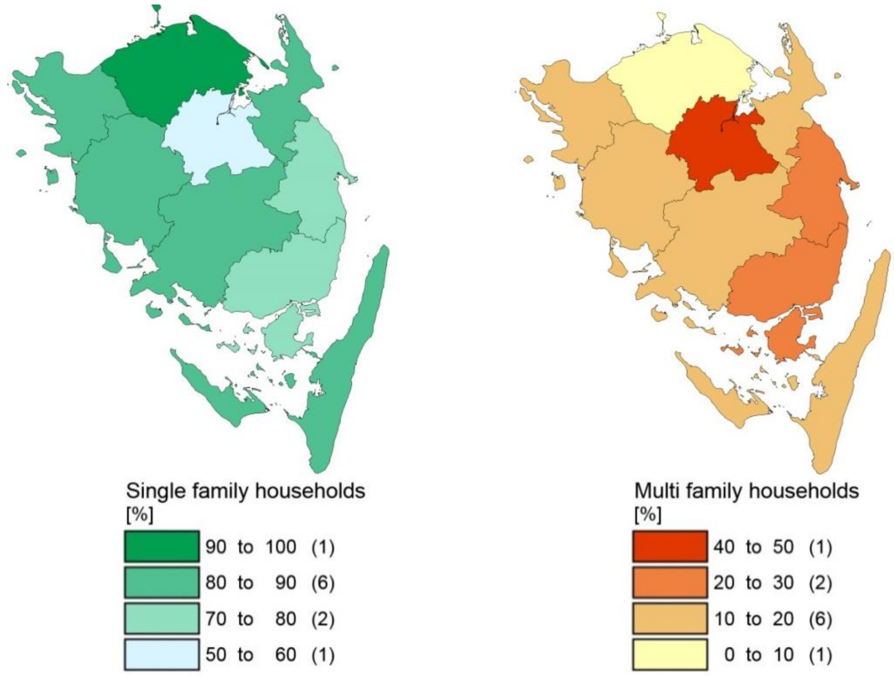


Figure 4: Map illustrating share of single family households (left) and multifamily households (right) in the 10 municipalities in the region of Funen, Denmark. The stronger the colour, the larger is the share of the specific type of households.

The high population density in Odense municipality is reflected in the very large share (44 %) of multi-family households. Most of the municipalities have a share of 10-15 % multi-family households. Svendborg and Nyborg municipalities have a slightly larger share (~25 %) and lie in between. Nordfyns municipality has the lowest share of multi-family households of 7 %. Overall the region counts 226,000 primary households (2014) divided between 73 % single-family households and 27 % multifamily households.

According to Danmarks Statistik other "uninhabitated" *(ubeboede)* housings are found in the municipalities. These are housings have no CPR number registered and thereby it is not a first priority address; it is secondary residences that have only part time use for example as vacation housing *(fritidshuse)*. Some municipalities within the catchment area are more affected by this than others, Figure 5.

Langeland is again standing out by having a lot of vacation housings and other secondary housings (40 %). Also Ærø and Nordfyns municipality have a large share of secondary housings (>24%), whereas most of the municipalities have around 10 % of secondary housings. Odense also stands out as the municipalities with the lowest relative share of secondary housing.

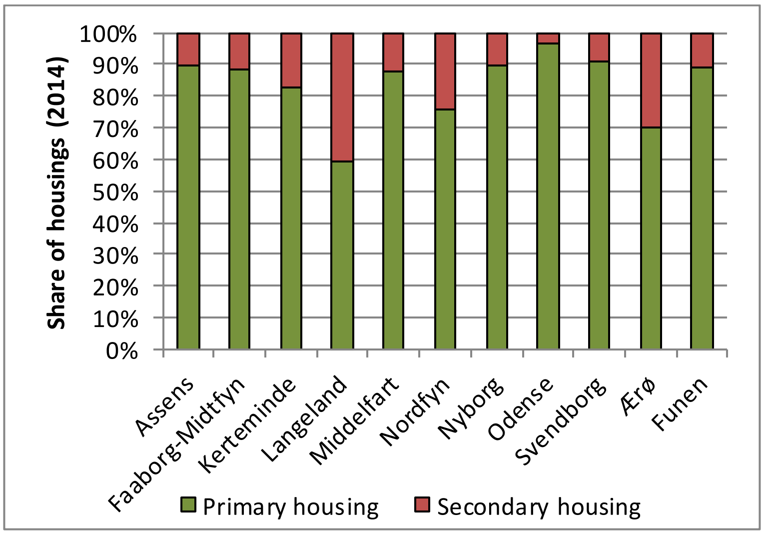


Figure 5: Ratio between primary and secondary housings in the 10 municipalities on Funen.

1.2.1.1 Sum-up:

- The region of Funen consists of 10 municipalities with 486,000 inhabitants and an average population density around 100 persons/km^2.
- Unequal distribution of population in the region of Funen means that each municipality faces different challenges in terms of collection in rural areas, in heavy populated areas and in touristic areas. The logistic task of implementing new collection systems in the municipalities will differ between the municipalities.
- A total of 226,000 households are included in the assessment and the ratio between single - and multi-family households that will be used for this purpose is 73 % single - and 27 % multi-family households. The assessments in Part 2 and 3 of this report will represent the region of Funen as a single unit, not differentiating between the local characteristics of each municipality.
- Secondary housings are occupied part time and waste will also be generated from these. However, in this report every calculation (when made per capita or per household) will represent households and citizens with their primary address within the municipality.

1.2.2 Waste collection schemes within the catchment area

Different collection schemes are available within the catchment area, and this section will be used to present the collection schemes within the different municipalities in the region.

To give an overview of the different collection systems available in each of the 10 municipalities on Funen Table 1 has been created. This shows some similarities and a lot of differences between the different municipalities. The information represents 2013 status (however it is 2014 for Kerteminde and Middelfart and 2012 for Ærø). Table 1 already excludes some of the other materials which will not be included in the further assessments, such as wood and other material which are typically collected at recycling centres.

The various collection schemes used in the municipalities can be categorized in three basic types of collection schemes: kerbside collection, cube system and recycling centres. Examples of these have been presented in Figure 6.

Figure 6: Examples of different collection schemes. Top: recycling centre with containers for several material fractions (Odense), Bottom left: kerbside bins ready for collection (Odense), Bottom right: cube system for glass (Odense).

The most basic system can be found in **Nordfyns** municipality. The system includes kerbside collection only of residual waste. Paper and packaging glass can be collected in public collection points (cubes) and the recycling centres receive every kind of material. **Langeland** municipality has similar basic system; this is though supplemented by scout collection of paper and cardboard.

Simple expansions of the basic system include kerbside collection of single fractions like paper or organics. **Odense** and **Assens** municipality both have kerbside collection of paper or paper/cardboard as well as options of public collection points (glass or paper/card. and glass) and recycling centres for all recyclable fractions. **Kerteminde** and **Nyborg** municipality are the only ones collecting vegetable food-waste kerbside in a voluntary scheme. Other than that Kerteminde municipality has the basic system in terms of cube collection options (glass and paper/cardboard) and recycling centres. Nyborg municipality on the other hand has a district based system of partly kerbside collection of paper/cardboard and plastics and scout collection of paper, cardboard and packaging glass. Also the cube system is slightly more advanced covering more material fractions (paper, cardboard, packaging glass, metals and plastics).

More advanced kerbside collection systems can also be found in **Faabrog-Midtfyn**, **Middelfart**, **Svendborg** and **Ærø** municipality. They all use a system of mono-stream collection of paper, cardboard, glass, metals and plastics in clear bags (bin for paper in Middelfart). Faaborg-Midtfyn, Middelfart and Ærø municipality has an official system with bags provided by the municipality, whereas Svendborg collects recyclables as part of a bulky waste collection scheme mostly as a service used in the rural areas. Svendborg municipality has additionally scout collection of paper. These municipalities all offer the standard cube collection of glass and paper.

It has been evaluated that material collected by scout collections will count as collected at recycling centres in the analysis, since scout collections are not a part of the official collection schemes.

Table 1: Schematic overview of collection schemes in the 10 municipalities on Funen; an “x” is marked whenever a system is available.

	Residual	Organics	Paper				Cardboard				Glass				Metal			Hard plastics			Foil plastics		Comments
	Kerbside	Kerbside	Kerbside	"Scout collection"	Cubes	Recycling center	Kerbside	"Scout collection"	Cubes	Recycling center	Kerbside	"Scout collection"	Cubes	Recycling center	Kerbside	Cubes	Recycling center	Kerbside	Cubes	Recycling center	Kerbside	Recycling center	
Assens	x		x		x	x	x		x	x			x	x			x			x		x	Paper and cardboard is collected as a mix fraction both kerbside and in cubes.
Faaborg-Midtfyn	x		x		x	x	x			x	x		x	x	x		x	x		x	x	x	Kerbside collection of recyclables in clear bags (single fraction). Participation is voluntary.
Kerteminde	x	x			x	x			x	x			x	x			x			x		x	Kerbside collection of organics is optional. It accounts for vegetable food waste and small garden waste. Paper and cardboard is collected as a mix in cubes (not intended).
Langeland	x			x	x	x		x		x			x	x			x			x			Plastic fraction is a mix of soft and hard.
Middelfart	x		x		x	x	x			x	x		x	x	x	x	x			x		x	Clear bags for separate material (Card./Metal/glass). Separate bin for paper. Few cubes in areas of sommerhousing.
Nordfyn	x				x	x				x			x	x			x			x		x	
Nyborg	x	x	x	x	X	x	x	x	x	x		x	x	x		x	x	x	x	x			Voluntary kerbside collection of vegetable food-waste. 2 districts have kerbside collection of mixed card/paper (in bin) and mono plastics (in bags). Scout collection covers the 3. district. Plastic fraction is a mix of soft and hard.
Odense	x		x			x				x			x	x			x			x		x	
Svendborg	x		x	x	X	x	x			x	x		x	x	x		x	x		x			Kerbside collection is part of "bulky waste" collection scheme. No separate collection of plastic foils.
Ærø	x		x			x	x			x	x		x	x	x		x	x		x		x	Kerbside collection in yellow/clear bags (single fractions / mixed paper/cardboard).

1.2.2.1 *Residual waste management*

The residual waste is currently incinerated directly, and three waste incineration plants handle the residual (and other combustible) waste from the municipalities; Odense Kraftvarmeværk A/S, Svendborg Kraftvarme A/S and Energnist (Kolding[3]). Odense CHP and Svendborg CHP are both located within the catchment area, whereas Energnist is located in Kolding (Jutland). Only Middelfart sends (most of) their residual waste to Kolding (77 % according to 2014 data). Table 2 gives an overview of the actors and the quantity/share of generated residual waste within the catchment area, that each of the actors handle.

Table 2: Overview of WtE actors and the quantity/share of residual waste handled by each of the actors

Waste incineration plant (WtE)	Quantity of residual waste [tonnes]	Share of the residual waste
Odense Krafvarmeværk A/S	82,687	72.6 %
Svendborg Kraftvarmeværk A/S	22,081	21.1 %
Energnist	7,022	6.3 %
Total	111,790	100 %

The quantities in Table 2 exclude small and large combustible waste collected at recycling centres.

Figure 7 illustrates from which areas the three identified WtE plants receive residual waste. Most of the waste is brought to Odense (42 % is generated in Odense municipality), which indicates that Odense CHP is by far the most important facility. Only the municipalities in the southern region of Funen (i.e. Langeland, Ærø, Svendborg and old municipalities of Ryslinge (Faaborg-Midtfyn) and Ørbæk (Nyborg)) send their residual waste for incineration in Svendborg, whereby having a plant in Svendborg reduces transportation. Having a close connection to Trekantsområdet (Jutland) Middelfart is the only municipality sending part of the residual waste outside the catchment area.

[3] Previously known as Trekantsområdets Affaldsselskab I/S

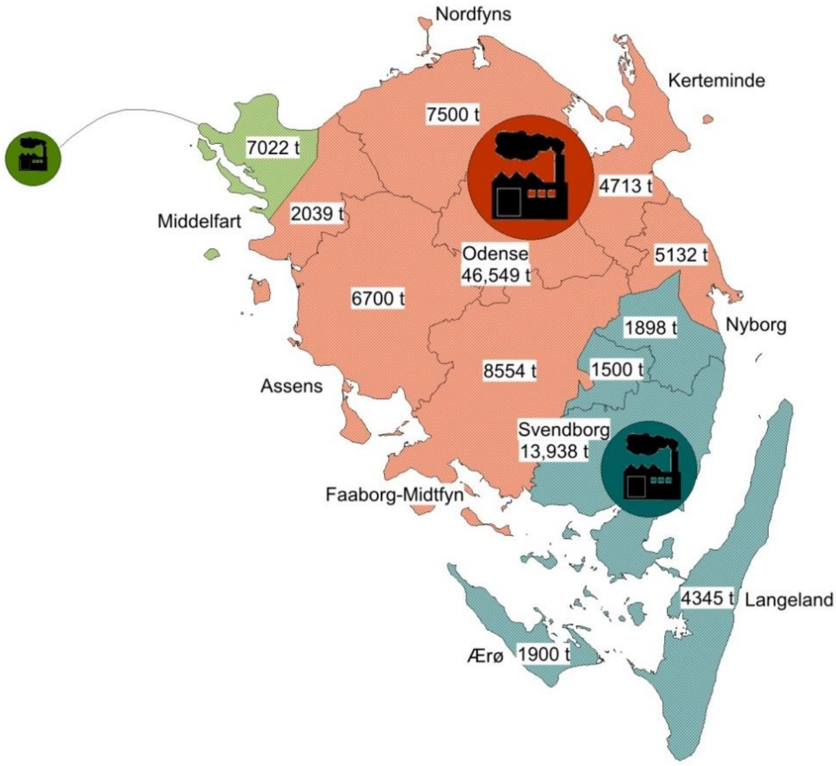


Figure 7: Map illustrating which WtE plants the municipalities apply in residual waste incineration. Quantities representing each municipality/district are noted in the respected area. Green: areas providing waste for Energnist in Kolding, Red: areas providing waste for Odense Kraftvarmeværk A/S, Blue: areas providing waste for Svendborg Kraftvarme A/S.

1.2.2.2 Recyclable waste management

Six fractions of recyclable material have been the focus in this study; paper, cardboard, glass, metals and soft/hard plastics. Also a small part of vegetable food waste is collected kerbside and composted together with garden waste by Klintholm I/S. Key actors have been identified in the waste management system. Because of business confidentiality and market based distribution it has not been possible to get detailed information on further distribution of the materials. Some actors serve as intermediaries, some pre-treats the waste, but none of them have an interest in sharing details of the following paths of the waste streams.

Figure 8 gives an overview of the actors in handling recyclable materials from Funen. Some actors have locations more places like H.J. Hansen Genindvindingsindustri A/S (Middelfart, Svendborg, Odense) and Marius Pedersen A/S (Svendborg, Odense) and, but for the sake of simplicity one actor will serve under one location (Odense).

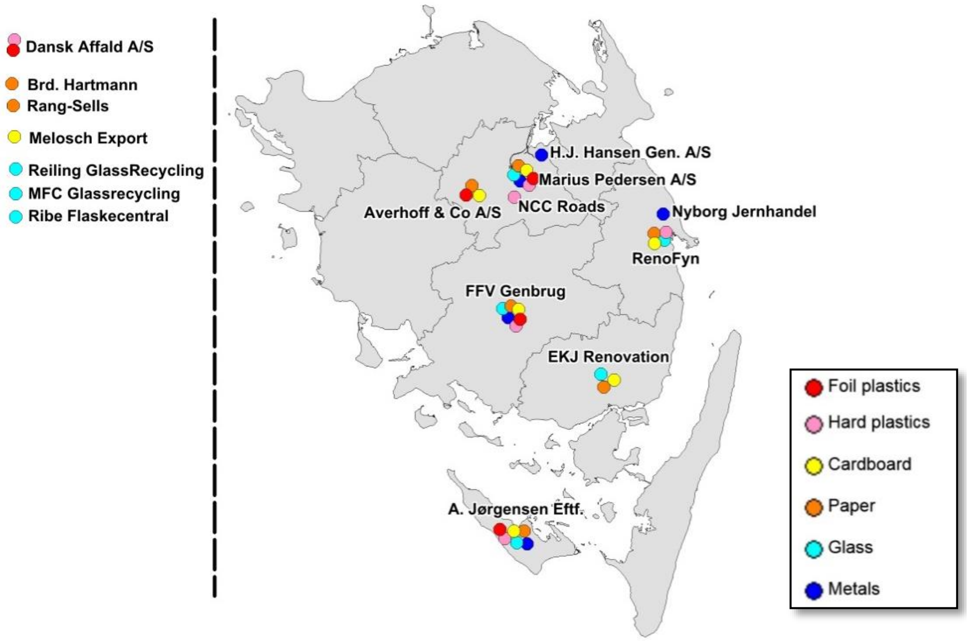


Figure 8: Actors in the waste management of recyclable material on Funen. The materials have been color-coded (see legend). Dots to the left of the dotted line symbolize actors outside the catchment area.

FFV Genbrug collects and sorts the recyclable material for further distribution in Faaborg-Midtfyn municipality. Anders Jørgensen Eftf. collects and transfers the recyclable material on Ærø and distributes it mainly to Marius Pedersen A/S (paper, cardboard, plastics, glass) and H.J. Hansen Geninvindingsindustri A/S (metals). Odense, Svendborg, Assens and Kerteminde municipality use Marius Pedersen A/S as their primary actor for most of the focal materials. The other municipalities use more actors for the different materials.

Based on a survey between some of the actors a tendency for final reprocessing has been formed. Paper is mostly sold to paper mills in Germany (or Sweden) and some of the paper is used for egg tray production at Brdr. Hartmann in Tønder (DK). Cardboard is generally not processed in Denmark and facilities in Germany are most likely to be the buyers for reprocessing. Ardagh Group remelts glass at a facility in Sealand (Holmegaard, DK) and is taking part of the waste glass, another share might be re-melted in Germany, but in this study it is assumed that all waste glass is re-melted in Denmark. The hard plastics are both distributed for further sorting of polymers and for reprocessing. These could probably both be carried out in Germany. Also reprocessing of plastic foils (LD-PE) could happen in Germany. Fe-metals are likely to be reprocessed in Turkey, whereas NF-metals are likely to be processed in Germany.

1.2.2.3 Sum-up:

- Currently the management approach towards the collection of recyclable material differs a lot among the municipalities. Most common is kerbside collection of paper, cube collection of paper and glass and recycling centres which receives all of the focal recyclable material fractions.
- Three waste incinerators are currently managing the residual waste generated in the region; Odense Kraftvarmeværk A/S, Svendborg Kraftvarmeværk A/S and Energnist.

- Currently most of the residual household waste (73 %) is incinerated in Odense and even 42 % of the residual waste is generated in Odense. Future placing of large sorting facilities and biogas production in Odense would therefore be the logic solution, and this was considered through the study.
- Reprocessing of the recyclables happens outside the region borders, and only pre-sorting and transfer happens within the borders.

1.2.3 Mass flow assessment: Waste generation and material recovery within the catchment area

The data collected from stakeholders in each of the municipalities have been summed up in this section. It covers quantities and tendencies in waste generation and material recovery. Funen will be handled as one unit without differentiating between the individual municipalities, but this will give an understanding of the existing efficiencies within each of the municipalities and serve as a platform for discussion later on.

1.2.3.1 Material flows in the 10 municipalities

Table 3 gives an overview of the data collection related to material flows in each of the 10 municipalities. The data represent material collection in 2013 (however it is 2014 for Kerteminde and Middelfart and 2012 for Ærø). 277,000 tonnes of waste considered as municipal waste is generated and collected per year in the region. This covers a number of material fractions from residual waste collected kerbside to recyclable material collected through various schemes and combustible waste collected at the recycling centres. As already presented in Table 1, Kerteminde and Nyborg municipality are the only ones having separate collection of the vegetable food-waste (organics). Also the fraction of foil plastics is not collected separately in three of the municipalities (Langeland, Nyborg, Svendborg). Langeland municipality has no separate collection of large combustibles; this fraction is crushed and mixed into the small combustible container.

Table 3: Overview of the material flows in each of the 10 municipalities [tonnes/year]

Material [tonnes/year]	**Assens**	**Faaborg-Midtfyn**	**Kerteminde**	**Langeland**	**Middelfart**	**Nordfyn**	**Nyborg**	**Odense**	**Svendborg**	**Ærø**
Residual waste	6,700	10,054	4,713	4,345	9,060	7,500	7,030	46,549	13,938	1,900
Organics			1,098				1,357			
Paper	2,001	2,230	774	688	2,443	1,044	1,584	10,541	2,155	216
Cardboard	574	492	389	195	416	218	362	1,585	452	144
Glass	468	790	458	268	520	500	532	3,598	895	125
Metals	1,161	1,444	654	421	1,129	825	616	3,181	1,161	131
Hard plastics	266	260	256	90	156	68	271	1,154	185	44
Foil plastics	88	79	30		65	37		14		1
Wood	2,030	2,861	1,172	505	1,341	1,610	1,105	9,388	2,217	281
Small combustible	1,341	2,511	916	919	1,184	1,052	1,170	5,117	3,494	259
Large combustible	572	445	314		907	426	885	708	89	105
Garden waste	6,167	10,000	3,400	1,209	6,241	5260	3,893	20,676	9,488	724
Total	**21,367**	**31,166**	**14,174**	**8,640**	**23,462**	**18,540**	**18,805**	**102,511**	**34,074**	**3,930**

The collection of different overall material fractions (recyclable, combustible, food-waste and compost material (garden waste)) in each of the municipalities are illustrated by pie charts in Figure 9. The size of the circles indicates the quantity of material collected in each of the municipalities. The food-waste collected in Kerteminde and Nyborg municipality contains a fair amount of small garden waste and is currently composted together with garden waste at Klintholm I/S. Separate kerbside collection of organics can though be included in the calculation of the recycling rate according to the national goal, and it has therefore been illustrated separately.

Odense is the municipality that generates the most waste per year, which corresponds to the large population. This also indicates that improving the recycling rates in Odense municipality would have a more significant impact on a regional/national level than improving the situation on Ærø would.

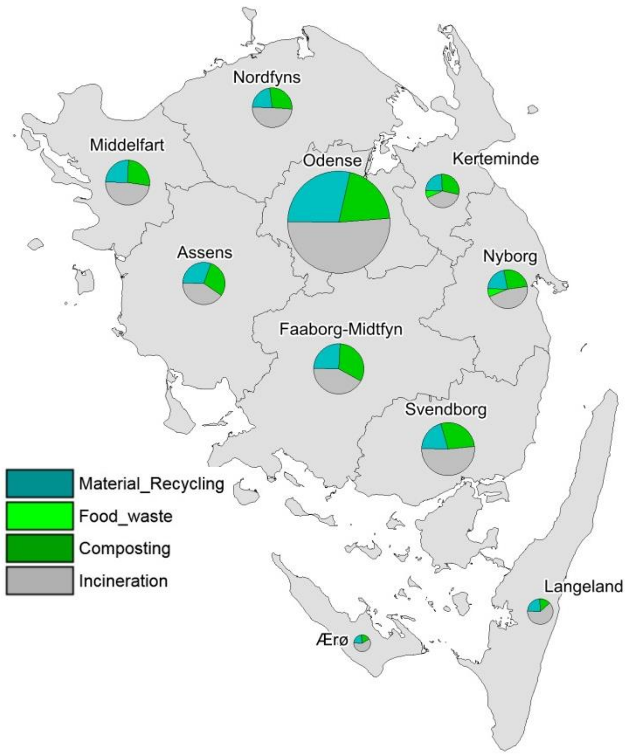


Figure 9: Map illustrating ratio (based on weight) between the collection of the overall material fractions in the municipalities. The size of the pie chart indicates the quantity collected.

1.2.3.2 Recycling rates according to the national resource strategy

The focal recyclable material of this assessment is paper, cardboard, glass, metals and plastics (hard and foil). Color-coded dots in relative size of collected quantities in each municipality are represented in Figure 10. Common for all of the municipalities is that the material fraction collected in largest quantity is paper. Also glass and metals are collected in relatively high amounts, whereas plastic collection/recovery represents the lowest amount.

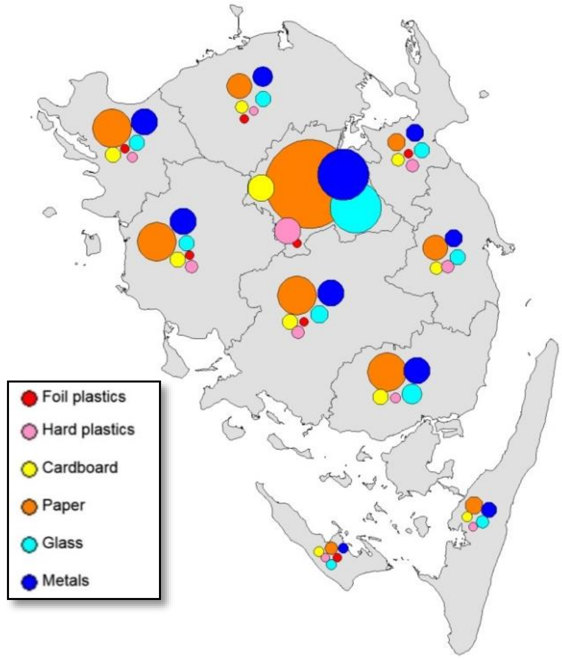


Figure 10: Illustration of quantity of collected recyclable material in each of the 10 municipalities on Funen. The materials have been color-coded, and the dots are relative in size in terms of quantity collected.

In order to give a more comparable overview of the collection rates of these materials in each of the municipalities a stacked bar chart has been created representing collected amounts per household per year, Figure 11. The chart to the left differentiates between material types, whereas the chart to the right differentiates between collection routes.

The municipalities have different collection rates and the ratio between the material fractions differs. 223 kg of the defined recyclable material is collected as an average per household in the region of Funen in a year. In general 30-53 % (avg. 40 %) of the recyclable materials collected in the municipalities is paper. 8-22 % (avg. 10 %) is cardboard, 10-19 % (avg. 16 %) is collected as glass, 16-31% (avg. 21 %) is collected as metals and lastly 4-11 % (avg. 6 %) is collected as hard and foil plastics.

The graph to the right indicates that kerbside collection comes typically second to the recycling centres in all municipalities, except in Middelfart. Primarily paper is collected kerbside. Cube systems tend to take a fair share of materials in the municipalities that do not have kerbside collection and this system is mainly used in the collection of glass and paper. Cardboard, metals and plastics can usually only be collected at the recycling centres. Options for collecting/disposing material close to the household could transfer the collection of some of the focal materials from recycling centres. Some of the material fractions (cardboard and metals) often come in larger pieces that would not fit totally in a kerbside bin, but more comprehensive property close collection would most likely facilitate the capture of materials which still go to the grey/residual bin.

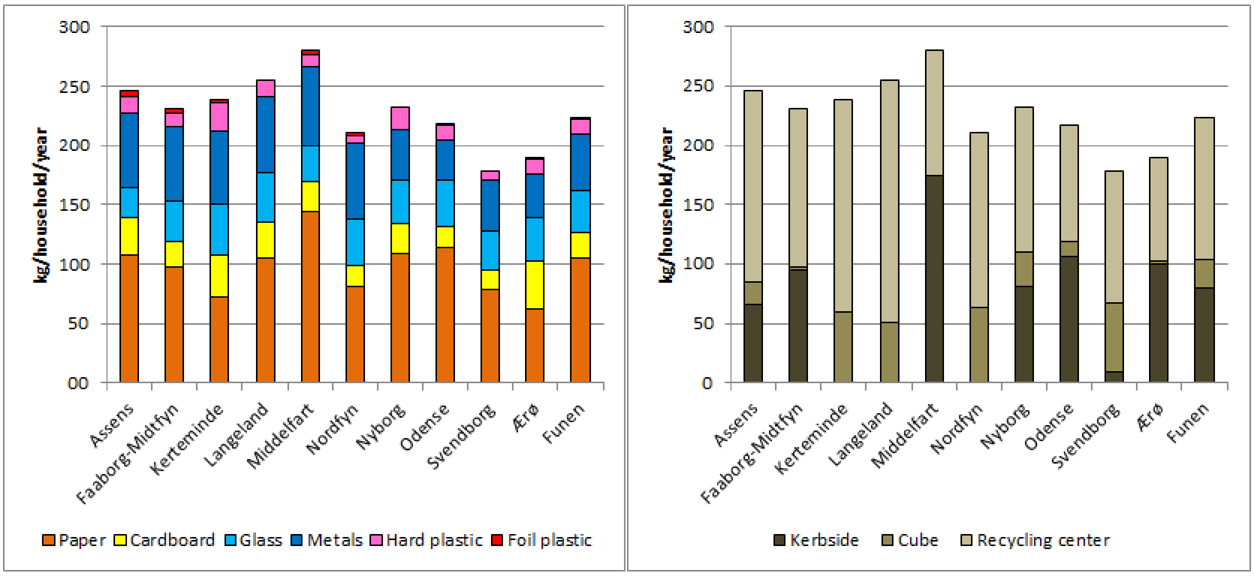


Figure 11: Comparing collection rates of recyclable material (kg/household/year) in the 10 municipalities. Left: Divided between material fractions (paper, cardboard, glass, metals, hard plastics and plastic foils), Right: Divided between collection routes (kerbside collection, cube system, recycling centres)

The varying recovery rates among the municipalities are difficult to explain. In some cases it could be because a larger potential of materials are left in the residual waste stream due to inefficient sorting, but it could also be due to different generation/use of the material fractions in the individual municipalities.

The recycling rates have been calculated according to our interpretation of the guidelines provided in appendix 5 of the resource plan (Miljøstyrelsen, 2014). The recycling rate is calculated as the share of recovered recyclable material of the sum of material collected both for recycling and incineration. Certain fractions are included in the calculation and there is a lot of confusion about how to apply it in the municipalities. In our calculation the following fractions have been included:

Recycling

- H02: organic waste (organisk affald)
- H05/H09: paper incl. newsprints (papir inkl. aviser)
- H06/H10: cardboard (pap/emballage pap)
- H08/H13: plastics (plast/emballage plast)
- H11: packaging glass (emballage glas)
- H12/H19: metals (emballge metal/jern og metal)
- H15/H30: wood (træ/emballge træ)

Incineration

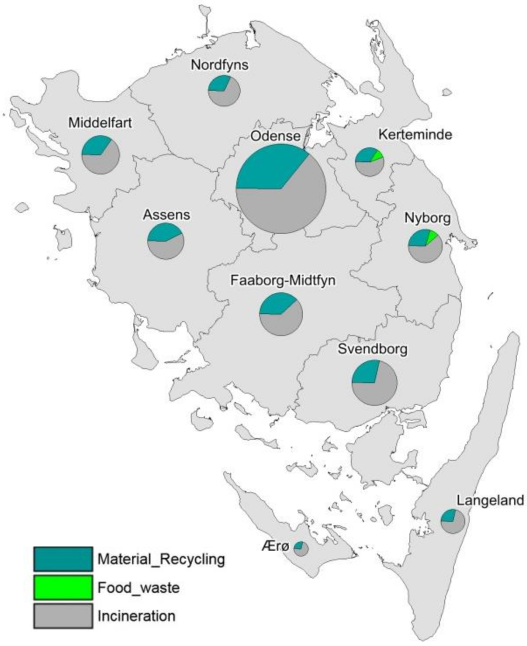
- H01: residual waste (dagrenovation)
- H03: combustible waste (forbrændingsegnet)

Other waste fractions like H07 (glass – window glass) included in the guideline has not been included in these calculations, whereby the result might differ from the internal calculations in the municipalities. This must therefore be seen as a conservative estimate of the recycling rates in the municipalities.

The recycling rate has been calculated and an overview is presented in Table 4 which is supplemented by an illustration. The recycling rate spans from 29-45 % and indicates that recovery of the specific material compared to the combustible share differs a lot between the municipalities. Separately collected biowaste contributes significantly to the overall recycling rates in Kerteminde and Nyborg municipality. The collection of biowaste is though not nearly as effective as it could be, since only vegetable food-waste is collected (incl. small garden waste, which constitutes a large share) and only part of the households is participating.

210,000 tonnes of waste included in the calculation is collected on Funen in a year of which 75,000 tonnes is collected for recycling. Funen overall has a recycling rate (based on these assumptions) of 36 %, which means that it is necessary to take action to reach the goal of 50 % recycling of household waste.

Table 4: Recycling rates in each municipality according to appendix 5 calculations (Miljøstyrelsen, 2014) supported by pie charts. The size of the pie chart indicates the magnitude of material collected.



Municipality	Recycling rate [%]
Assens	43.3 %
Faaborg-Midtfyn	38.5 %
Kerteminde	44.8 %
Langeland	29.2 %
Middelfart	35.2 %
Nordfyn	32.4 %
Nyborg	39.1 %
Odense	36.0 %
Svendborg	28.7 %
Ærø	29.4 %
Funen, Total	36.0 %

1.2.3.3 Defining the functional unit

In the following system modelling not all fractions will be included, which implies that recycling rates mentioned later on will not represent the appendix 5-guidelines of calculating this (unless it is specified).

Only waste generated and disposed of with a daily frequency (excluding bulky items and long lasting products) will be included. This means that large combustibles as well as wood and garden waste will be excluded from the modelling since changes in the collection system towards increased kerbside collection is evaluated not to have an impact on the management of these. The small combustible waste constitute a mixture of materials (<1 m in size) which cannot be sorted in other containers at the recycling centres, but are safe to dispose through incineration. Studies however show that the small combustible waste fraction contains 30-50 % materials wrongly sorted, i.e. which could have been sorted in the containers for recycling (Larsen et al., 2011, Petersen, 2011). A new kerbside collection system which facilitates better sorting at the household, will probably claim shares of this waste stream, however no monitoring/characterization of the composition before and after implementing kerbside collection schemes is available in order to make an estimate of this. The small combustible waste stream has therefore also been excluded in this assessment. Also the metal fraction collected at recycling centres has been adjusted. A characterization study show that around 25 % of the metal fraction collected at Danish recycling centres constitutes smaller items i.e. cans, kitchenware, toys, tools, nails etc. (Hycks et al., 2013). These items would fit a kerbside bin whereas the larger pieces of metal still would be collected through recycling centres.

This leaves us with a total of 157,000 tonnes of daily generated household waste per year covering paper, cardboard, glass, metals, plastics, food-waste and residual waste *(dagrenovation)* collected kerbside, through cube systems and at recycling centres. Table 5 gives an overview of which material fractions and quantities has been included in the functional unit compared to the ones discussed in the previous sections.

Table 5: Overview of material fractions and quantities divided between different definitions; total MSW, Appendix 5 categories and the functional unit applied in the study

Material fraction	Total municipal waste [tonnes/year]	Appendix 5 [tonnes/year]	Functional unit [tonnes/year]
Residual waste	111,789	111,789	111,789
Food/biowaste	2,455	2,455	2,455
Paper	23,675	23,675	23,675
Cardboard	4,827	4,827	4,827
Glass	8,154	8,154	8,154
Metals	10,723	10,723	3,043
Hard plastic	2,750	2,750	2,750
Foil plastic	314	314	314
Wood	21,971	21,971	
Small combustible	17,779	17,779	
Large combustible	5,174	5,174	
Garden waste	67,058		
Total	276,669	209,611	157,007

In order to model the systems it has been necessary to estimate the full potential of the focal recyclable material incl. organic waste (food-waste), i.e. additionally define what is left in the mixed residual waste stream. Since none of the municipalities have performed a characterization of their residual waste stream, it has been difficult to specify the potentials in each municipality. An average residual waste composition (Petersen and Domela, 2003) has therefore been used in the modelling. An average potential per household in the region of Funen has been defined for each material fraction based on a combination of the already collected/recovered material and the remaining material within the residual waste stream.

The calculated potential has been compared with the potentials estimated by the EPA (Møller et al., 2013), Table 6. In general, the calculated potentials are higher than the ones estimated by the EPA. The foundation of calculating the potentials are not identical due to different approaches. The residual waste stream in this project has been modelled using an average composition and the aggregated material fractions (especially for plastics) might not match the definition from the EPA completely. It is evaluated that the calculated potentials are within reason and the work will continue based on these.

Table 6: Potentials of different material fractions [kg/household/year] including average recovery on Funen

	Potential by EPA[4] [kg/household/year]		Calculated potential [kg/household/year]	Avg. recovery on Funen 2013 [kg/household/year]
	min	max		
Paper	161	162	153	105
Cardboard	25	28	57	21
Glass	33	38	50	36
Metal	16	19	30	13
Plastics	33	38	60	14
Organic	218	302	256	11
Residual	122	135	89	494
Total	608	722	694	694

Each of the material fractions have been illustrated together with an average potential (the horizontal lines) incl. an average recovery per household in the 10 municipalities on Funen (represented by bars), Figure 12.

Paper and glass are the fractions collected closest to their potential, whereas cardboard and metals have a slightly lower recovery. Most of the plastics are to be found in the residual waste stream. Biowaste is only collected in two municipalities (and in modest amounts) and the biowaste is therefore currently also almost exclusively found in the residual waste stream.

This Figure 12 (particularly the overall Funen values, see also Table 6) illustrates the left over potential of recovery. Changes in the collection system would most likely improve the recovery of certain materials.

On an average 694 kg of household waste is generated per household in the region of Funen per year (according to the definition of the functional unit). 200 kg/household/year is separately collected either for material recycling (paper, cardboard, glass, metals, plastics) or for composting (biowaste). A potential of 400 kg/household/year, mainly represented by organic waste, is still found within the residual waste stream.

[4] (Møller et. al., 2013)

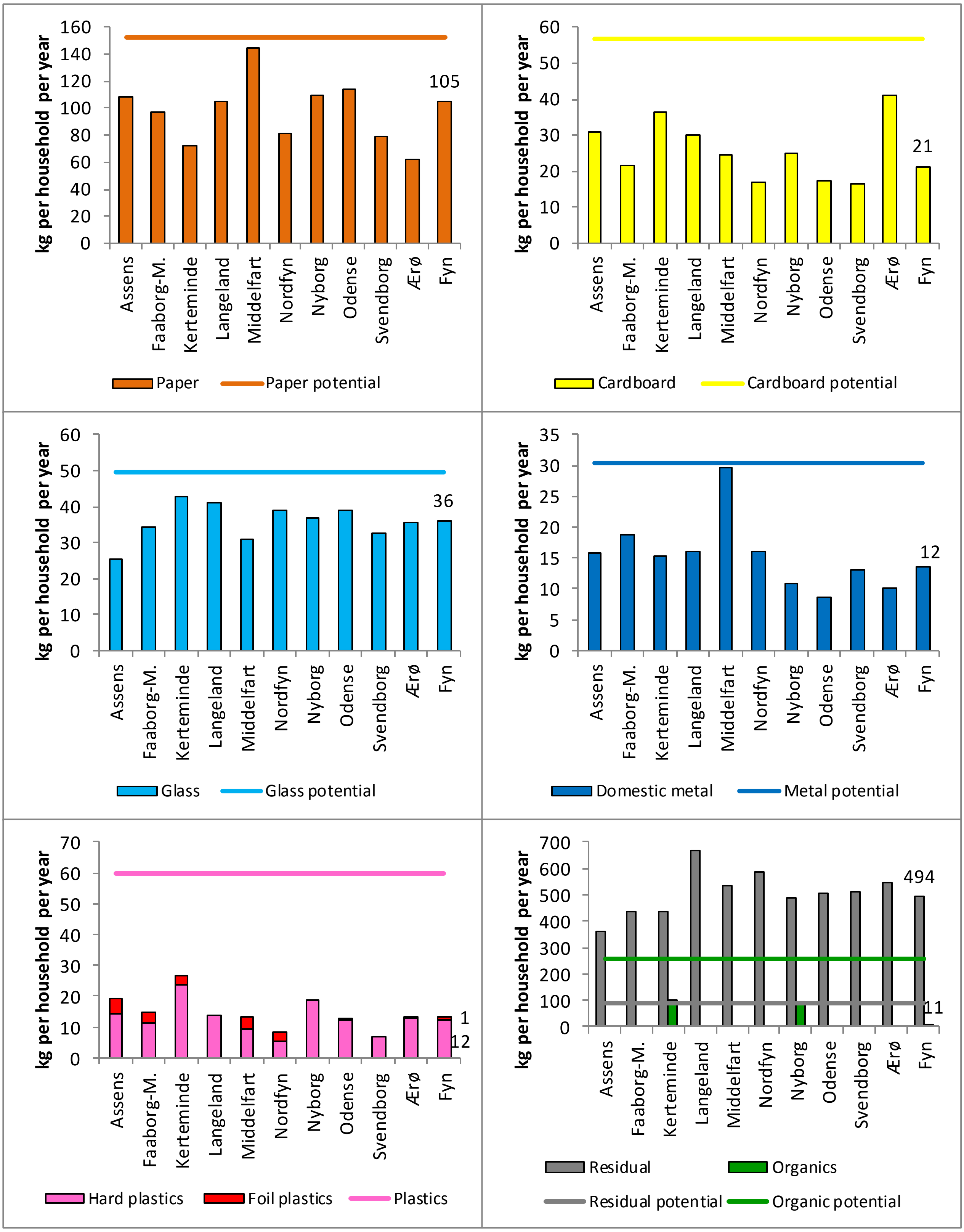


Figure 12: Amount of recovered material (paper, cardboard, glass, metals, plastics and organics/residual waste) per household per year in each municipality and Funen as a whole including an indicator of the average potential amount

Table 7 gives an overview of how much of each material fraction is recovered compared to the average potential. The recovery efficiency for paper (60-70 %) and glass (70-80 %) are high in most municipalities. The efficiency of cardboard (40-50 %) and metal (40-50 %) recovery is medium in most municipalities. The recovery efficiency of metals in Middelfart municipality is though impressively high (almost 100 %), which mainly is due to the large amount of metals collected kerbside in the municipality. Only around 20 % of the plastics are recovered.

Table 7: Overview of material recovery efficiencies in each material fraction based on the average potential for each of the 10 municipalities incl. an average for Funen

	Paper	Cardboard	Glass	Metal	Plastics
Assens	71 %	55 %	51 %	52 %	32 %
Faaborg-Midtfyn	64 %	38 %	69 %	62 %	25 %
Kerteminde	47 %	64 %	86 %	50 %	44 %
Langeland	69 %	53 %	83 %	53 %	23 %
Middelfart	95 %	43 %	62 %	98 %	22 %
Nordfyn	54 %	30 %	79 %	53 %	14 %
Nyborg	72 %	44 %	74 %	36 %	31 %
Odense	75 %	30 %	79 %	28 %	21 %
Svendborg	52 %	29 %	66 %	43 %	11 %
Ærø	41 %	73 %	72 %	34 %	21 %
Funen, Total	**69 %**	**38 %**	**73 %**	**44 %**	**23 %**

1.2.3.4 Sum-up:

- 277,000 tonnes of MSW is collected in the municipalities per year. This includes garden waste, wood, small and large combustibles, plastics, metals, glass, cardboard, paper, food-waste and residual waste. Garden waste, wood, small and large combustibles as well as part of the metals collected as bulk on the recycling centres have been excluded from the modelling since changes in kerbside collection schemes will not affect the management of these fractions. In total 157,000 tonnes of household waste is included in the modelling, and this has been used as the functional unit of the study.
- According to our interpretation of the appendix 5 calculation of the recycling rate in the municipalities is between 26-45 %. Funen as an average has a recycling rate of 36 %, which means that actions needs to be made in order to reach the national goals of 50 % in 2022.
- Based on limited information on the composition of the residual waste stream the calculated potentials (Table 6) will serve as a basis for the material flow modelling.
- Based on the defined functional unit 694 kg of daily household waste is generated per household in the region of Funen per year. Currently 189 kg recyclable material (paper, cardboard, glass, metals, plastics) and 11 kg biowaste is collected per household per year. Compared to the potential the recovery of paper and glass is high (~70%), whereas the recovery of cardboard, metals (~40%) and especially plastics (~20%) are low. The recovery of biowaste is almost negligible compared to the potential (~4%).
- The effects of system changes that will be modelled in the next section (Part 2) regarding separate collection of recyclable materials will not be equally significant in all of the municipalities because we can already see that a few municipalities have already quite efficient systems.
- Property close collection will limit the need for bringing the focal material to the recycling centres. Changing the systems towards increased kerbside collection will therefore lead to an exclusion of recycling centres in the system modelling.

2 Part 2: System modelling and carbon footprint assessment

Part 2 of this report documents the methods used and results obtained following the mass flow analysis and carbon footprint assessment of the current/reference waste management system in the region of Funen and alternative systems designed to reflect different degrees of and solutions to separate collection, automated central sorting, materials recovery for recycling, biowaste separation with different uses of the bio-fraction, and waste incineration for energy recovery.

2.1 Methods

The method section goes through the foundation of the system simulation and carbon footprint assessment as well as the system boundaries introducing foreground and background systems. This section also contains a detailed lifecycle inventory (LCI).

2.1.1 Waste management systems simulation

The existing waste management systems in the 10 municipalities on Funen (described in Part 1 of this report) have been aggregated to one system which represents the whole region. Starting from this baseline system, 23 more systems were designed, accounting for changes in separate collection and the treatment of the residual waste stream. The systems are described in section 2.1.4 in this report.

A spreadsheet-based mass balance model was used to simulate the process chains in all described systems. The model simulated the transfer and conversion of waste streams and fractions through the entire system, based on the input waste composition and associated physical and chemical characteristics. Waste generation and collection has been distinguished between type of residence, i.e. single - and multi-family residences, thus accounting for slight differences in source separation behaviour, waste composition and waste generation rate. The model input constituted the waste generated in one year in the region, in the amount of 157,007 tonnes, defined as daily generated household waste (described in Part 1).

2.1.2 Carbon footprint assessment

The mass flow simulation model allows for detailed accounting of the carbon content of the waste throughout the simulated systems, i.e. from waste generation to substitution of energy and materials on their respective markets. This enabled the accounting of all direct Green House Gas (GHG) emissions in the systems and their conversion to CO_2 equivalents. All system exchanges (i.e. consumptions and avoided energy and materials) were also converted to CO_2 equivalent burdens or savings. The systems were evaluated and compared on basis of consequential life cycle assessment methodology (CLCA), thus all processes reacting to the changes implemented in waste management systems were included (as far as possible) and so-called marginal supplies/marginal data was used in the modelling of system interaction.

All material and energy flows, as well as system burdens and savings, are related to a **functional unit (FU),** defined as *management (including collection, transport, treatment and final disposal of residues) of the yearly generation of 157,007 tons of daily generated household waste (wet weight) collected in the region of Funen, Denmark.*

The metric used to compare the systems is global warming potential (GWP100, kg CO_2 eq., aggregated over a 100 years), calculated on the basis of the latest Assessment Report of the Intergovernmental Panel for Climate Change (IPCC, 2013). The global warming factors (GWF) of significant substances were as follows for fossil emissions: CO_2=1, CO=2, CH_4=34 and N_2O=298.

GWP100 potentials (coefficients) were facilitated by the LCA software SimaPro 8.0.2. Background life cycle inventory (LCI) data was retrieved from the Ecoinvent v.3 database (Swiss Centre of Life Cycle Inventories), whereas foreground LCI data (system specific) was compiled from multiple sources, including municipalities own accounting systems and green accounts from downstream waste operators.

2.1.3 System boundaries

As a simplification of the complexity of the real world, it is possible to analyse complex systems by dividing them into ***foreground systems***, for which we want to provide decision support regarding their development, and ***background systems***, which impact or govern the effects of decisions taken regarding foreground systems.

In the analysis of waste management systems, as in this case, the foreground system comprises all waste management activities from waste generation, through treatment and recovery of materials and/or energy, to the point where these ***functional outputs*** are interacting/are exchanged with the background systems (the background economy and markets). The background systems represent the economic activities (e.g. energy production, material production) which exchange materials and energy (including the functional outputs) with the foreground. In this study, waste management system interactions with four main markets have been included: (1) energy and fuels production, (2) primary material production, (3) digestion co-substrates, and (4) combustible waste market.

2.1.4 Foreground systems and system variations

A total of 24 foreground systems have been designed and modelled in this study, Table 8.

Table 8: Matrix of systems modelled in the assessment; SF= single-family, MF = multi-family

Systems archetypes	**Separate collection**	**Treatment of remaining residual waste**			
		WtE: Incineration CHP	*CS-ADwet: Central sorting with wet digestion*	*CS-ADdry: Central sorting with dry digestion*	*CS-Biodry: Central sorting with biodrying*
System 0	Existing schemes	0-WtE	0-CS-ADwet	0-CS-ADdry	0-CS-Biodry
System 1	Existing schemes + Biowaste SF	1-WtE	1-CS-ADwet	1-CS-ADdry	1-CS-Biodry
System 2	Existing schemes + Biowaste SF and MF	2-WtE	2-CS-ADwet	2-CS-ADdry	2-CS-Biodry
System 3	Dual-stream	3-WtE	3-CS-ADwet	3-CS-ADdry	3-CS-Biodry
System 4	Dual-stream + Biowaste SF	4-WtE	4-CS-ADwet	4-CS-ADdry	4-CS-Biodry
System 5	Dual-stream + Biowaste SF and MF	5-WtE	5-CS-ADwet	5-CS-ADdry	5-CS-Biodry

2.1.4.1 Main system archetypes based on changes in source separation

System 0 – no change in source separation

This system is based on the existing collections schemes in the region and reflects the data collected from the municipalities (reference year 2013) regarding collection and management of recyclable materials and residual waste. This includes, thus, the small amount of biowaste being collected and composted in two municipalities.

System 1 – Source separation of biowaste in single-family residences

In this system the existing collection schemes regarding recyclable material are not changed. But in addition to existing schemes, biowaste collection is instituted in all single-family residences throughout the region. Existing collection of biowaste is overruled in advantage of this system change. The source separation efficiency for the bio-fraction of the waste was set to a conservative 60% (of food-waste generated). The composition modelled for the bio-bin reflects a content of miss-sorted materials (i.e. non-organic materials) of 5 wt.-%, based on a typical range from 1 to 10 wt.-% (Bernstad et al., 2013, Hansen et al., 2007), which needs to be removed through pre-treatment prior to anaerobic digestion. The modelled pre-treatment consists of a wet pulping and separation process (Lorentzen et al., 2013, Naroznova et al., 2013).

The reject from pre-treatment is sent to the WtE plant while the recovered biomass (biopulp, dry matter content of 15 %) is mono-digested in a local biogas plant, considering a CH_4 yield of 350 Nm^3 per tonne of volatile solids (VS) (Davidsson et al., 2007). The biogas produced is upgraded close to natural gas grade, and hence forth called biomethane. Biomethane can be stored in the gas grid and be used according to demand patterns. Biogas upgrading was added based on data from Bernstad and Jansen (2011). Flexible use of biomethane for electricity production was modelled using gas motors with efficiencies of 40% (electricity) and 45% (heat).

The other output, the digestate, is stored, and when appropriate, applied on agricultural fields as an organic fertilizer, thereby partly substituting mineral nitrogen (N), phosphorus (P) and potassium (K). The modelling of digestate storage, application, fertilizer substitution and soil C changes are partly based on the work of Hamelin (2013).

System 2 – Source separation of biowaste in both single- and multi-family residences

This system is the same as System 1, with the addition that biowaste is being collected in both types of residences, i.e. in all residences throughout the region. The biowaste source separation efficiency was set to 50 % in multi-family residences. The bio-waste collected in multi-family residences is typically more contaminated than for single-families, therefore a contamination level of 10 % was used in the model. All steps in the management of the new stream are the same as in System 1.

System 3 – Dual-stream recyclables

In this system the existing collection schemes for recyclable materials in the region are replaced with a single new uniform scheme. This is a kerbside dual-stream scheme, which has already been adopted in large parts of Jutland and to which also one of the municipalities on Funen has recently switched to.

The dual-stream collection consists of: (1) a mixed stream of paper, cardboard and plastic foils, and (2) a mixed stream of glass, metals and hard plastic containers. In the case of single-family residences, the two mixed material streams are stored together in a dual-chamber kerbside bin, and collected with the use of specific dual-compartment collection trucks. Large containers are provided instead to multi-family residences. The two streams are subsequently sorted into single materials in a specialized central sorting plant (Vojens, Denmark) and sold to international markets.

The source separation efficiencies set for the six materials included in this scheme are based on Cimpan et al. (2015b).

In this system biowaste is not source separated except for the two municipalities already having a partial collection of biowaste.

System 4 – Dual-stream and source separation of biowaste in single-family residences

This system retains the dual-stream collection of commingled recyclables, and biowaste collection in single-family households is added. The characteristics and management of the biowaste stream is the same as in System 1.

System 5 – Dual-stream and source separation of biowaste in both single- and multi-family residences

This final system incorporates all the changes introduced in the previous two systems, with the addition of biowaste collection in multi-family residences. All separately collected streams are managed as described in the previous systems.

2.1.4.2 System variants based on residual waste treatment

WtE – Residual waste to incineration WtE

In this first variant, residual household waste is sent to the three incineration CHP plants serving the region today (in Odense, Svendborg and Kolding). CHP efficiency was based on 2012-13 green accounts from the three plants.

CS-ADwet – Residual waste to Central sorting (CS), organics treatment and wet anaerobic digestion

Although future agreements between municipalities and waste incineration plants are difficult to predict, in this study it will be assumed that all residual waste generated will be managed inside the region.

In this variant, all residual waste in the region is sent to a central sorting facility in Odense. Here it undergoes a series of mechanical and automated separation processes, the objectives of which are to produce three material outputs: (1) metal and plastic concentrates for recycling, (2) storable RDF for energy production, and (3) a biopulp for anaerobic digestion.

While (1) and (2) constitute a general objective shared with the following two system variants, (3) is the defining aspect for this system variant. Specifically, in this variant the stream of concentrated organics resulting from the mechanical processing is further treated in a wet pulping process (the same pre-treatment used with biowaste from separate collection). Thus the output is a refined organic pulp that is used in wet anaerobic digestion.

The digestion residues are dewatered, similar to sewage sludge today, and the resulting sludge is transported to the local incineration facility.

The RDF produced in the central sorting facility was modelled as fully utilized for energy production in the Odense incineration plant. In reality, RDF could be also transported and used in Svendborg, however Odense was chose as a default, mainly because of the significantly higher energy recovery efficiency.

CS-ADdry – Residual waste to CS and organics dry anaerobic digestion

In this variant, all residual waste in the region is sent to a central sorting facility in Odense. Output (3) however constitutes the stream of concentrated organics (no additional treatment) which is directly fed into a dry anaerobic digestion facility on site. The digestion residues after this process are incinerated.

CS-Biodry – Residual waste to CS and organics biodrying

In this variant, all residual waste in the region is sent to a central sorting facility in Odense. Output (3) however constitutes the stream of concentrated organics (no additional treatment) which is directly fed to biological drying units on site. In this process part of the easily degradable organic matter is consumed (degraded) and the moisture content of the material stream is reduced to 20-25 %. The final output is an RDF which is baled and stored for later use in energy production.

2.1.5 Background systems

The alternative foreground systems and their variation described in the former section are, then, modelled on the basis of the background system within which they exist, and with which they interact. The essential background systems comprise:

- The energy systems (grids) of heat and electricity
- Manure biogas systems, agricultural soil systems and mineral fertilizer productions
- Virgin material production systems of recovered material fractions
- Virgin biomass production and the origin of this biomass
- Alternative waste management in landfill in scenarios with waste import

The interactions with these background systems are of key importance, and therefore the assumed nature of the background systems is decisive to the results. But we also know that these backgrounds systems change over time, and some of the key systems such as the energy system, virgin biomass production and waste management systems in general (including landfilling) are expected to change very significantly over the next decades. In order to ensure a robust comparison of alternative waste management systems and to provide a robust assessment for investment decisions, we must, thus, compare alternatives against these background systems as they can be expected to develop over time.

2.1.5.1 Continuous and flexible production of heat and electricity

In this work we place energy production from waste in two categories: continuous and flexible. The categorization is important because both the heat and electricity systems respond differently to continuous and flexible outputs of heat/electricity to the grids. A continuous production will replace one type of electricity or heat, whereas a flexible production (i.e. a production specifically supplied to the grids in times of the highest demand for heat/electricity) will replace a different type of heat/electricity. Definitions for energy from waste:

- **Continuous electricity** or baseload power production is associated with power plants with continuous operation and supply of electricity throughout the year, with breaks only for planned maintenance or service. Power produced by waste incineration plants falls largely under this category. However, modern incineration plants can adjust their operation considerably in a matter of hours by lowering or raising their capacity (between 70 % and 100 % load) and sometimes by adjusting the ratio between heat and electricity (condensing plants). For this reason, a flexibility factor has been associated with the waste CHPs in the systems.

- **Flexible electricity** represents a balancing power production, and is associated with power plants which can operate based on market demand, i.e. can fully start or shut down in a matter of minutes. Biomethane stored in the natural gas grid, or otherwise, is assumed to be used in the future for electricity production in this way.

- **Continuous heat,** accounts for the heat generated from waste incineration (together with electricity) and generated in the utilization of biomethane. In the latter case heat is more or less a byproduct of flexible electricity production, but does not have any flexible attributes. Continuous heat is assumed, in all three time perspectives, to avoid a mix in the ratio of 50:50 of marginal continuous and flexible heat production in the warm and respectively in the cold part of the year.

- **Flexible heat** here accounts for heat generation from combustion of RDF in waste incineration plants. RDF is assumed prioritized (stored) for heat generation in the cold part of the year, and therefore flexible heat avoids the production of the respective heat marginal. If electricity is generated together with heat from RDF, it is categorized similarly with regular electricity from incineration (i.e. continuous).

2.1.5.2 Time perspectives

As previously introduced, the background systems surrounding Danish waste management systems are undergoing important structural changes, most importantly the gradual transition from fossil-based to renewable-based energy. Waste management infrastructure changes imply considerable capital investment, which is typically recovered by maximizing lifetimes. For example, lifetimes of plants can extend from 20 years (sorting plants) to 30-40 years (WtE facilities). It is therefore crucial to consider future changes in the background systems when taking decisions regarding waste management in order to avoid lock-in effects.

The time scope considered in this work is 2012 to just beyond 2050. The timeline was broken down into four periods in accordance with the key milestones of Danish energy policy, i.e. 2012-2020, 2020-2035, 2035-2050 and beyond 2050. The key milestones considered were: (1) wind power makes up 50 % of electricity consumption in 2020, (2) coal is completely phased out in 2030, and (3) all heat and power is renewable in 2050. However, these milestones are expected to be relaxed to some extent by the new Danish Government (autumn 2015) and therefore the related background electricity and heat marginal in the four time periods were modified compared to the work by Wenzel et al. (2014), to include a small portion of fossil energy untill 2050. The Beyond 2050 time perspective then represents a fully renewable energy scenario.

The flexibility factors associated to waste incineration denote how much of the power produced is assumed to replace other regulating power on the energy market. The factors were: 30% in the Mid-term, 15% in the Long-term and 5% in the Beyond 2050 time perspectives. These factors are rough estimates which consider the decreasing "window of opportunity" over time, i.e. times when incineration can contribute with flexible power. These times decrease as renewable (wind and solar) cover more of the early power consumption.

Table 9: The four time periods and associated background electricity and heat marginals

		Electricity	Heat
Present (2012-2020)	*Continuous*	100 % coal power	100 % natural gas
	Flexible	100 % coal power	100 % natural gas
Mid-term (2020-2035)	*Continuous*	10 % coal, 5 % natural gas, 18 % biomass[5], 2 % solar and 64 % wind power	50 % heat pumps and 50 % natural gas
	Flexible	100 % coal power	100 % natural gas
Long-term (2035-2050)	*Continuous*	5 % coal, 5 % natural gas, 15 % biomass[6] and 75 % wind and solar power	50 % heat pumps, 25 % biomass and 25 % natural gas
	Flexible	25 % coal, 25 % natural gas, 50 % biomass[6]	50 % biomass and 50 % natural gas
Beyond 2050	*Continuous*	100 % wind and solar power	80 % heat pumps and 20 % biomass
	Flexible	100 % biomass[6]	100 % biomass

2.1.5.3 Biowaste from separate collection as a co-substrate in manure-biogas

As a baseline, the biowaste collected separately from households is digested in dedicated plants. However, considering the Danish targets on boosting manure-biogas, it is valuable to quantify possible benefits assuming that biowaste can contribute to achieving these targets.

In Denmark a target has been launched to achieve 50 % use of animal manure for biogas by 2020, as compared to the present use of 7- 8 %. Under current framework conditions, projections show that only between 20 and 35 % use will be achieved until 2020 (Jacobsen et al., 2013). One of the main barriers to expansion is related to biomass, i.e. it is increasingly difficult to find suitable biomass to supplement slurry in order to achieve adequate and economically feasible gas production.

In a consequential perspective, the biowaste made available by source separation of food waste from households can constitute a co-substrate to manure, thereby enabling extra manure quantities to be digested and/or substituting for the use of other marginal co-substrates, such as energy crops. The former can be valid in all three time periods, under the assumption that 100 % use of manure for biogas will not be achieved even in 2050.

The model has been used to produce system results, alongside baseline biowaste mono-digestion, for system variants where biowaste is co-digested with manure, thus avoiding reference manure management, or replacing the production of an alternative co-substrate for manure-biogas, namely maize.

Based on consequential LCA rationale, the benefits and burdens of the extra manure-biogas production were weighted against the burdens and savings associated with conventional manure management, which

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[5] The biomass marginal is used in direct combustion CHP

[6] The biomass marginal is used in wood gasification with syngas reforming to SNG stored and used for flexible power

is storage and application on land without any additional treatment, in the way described in Hamelin et al. (2013).

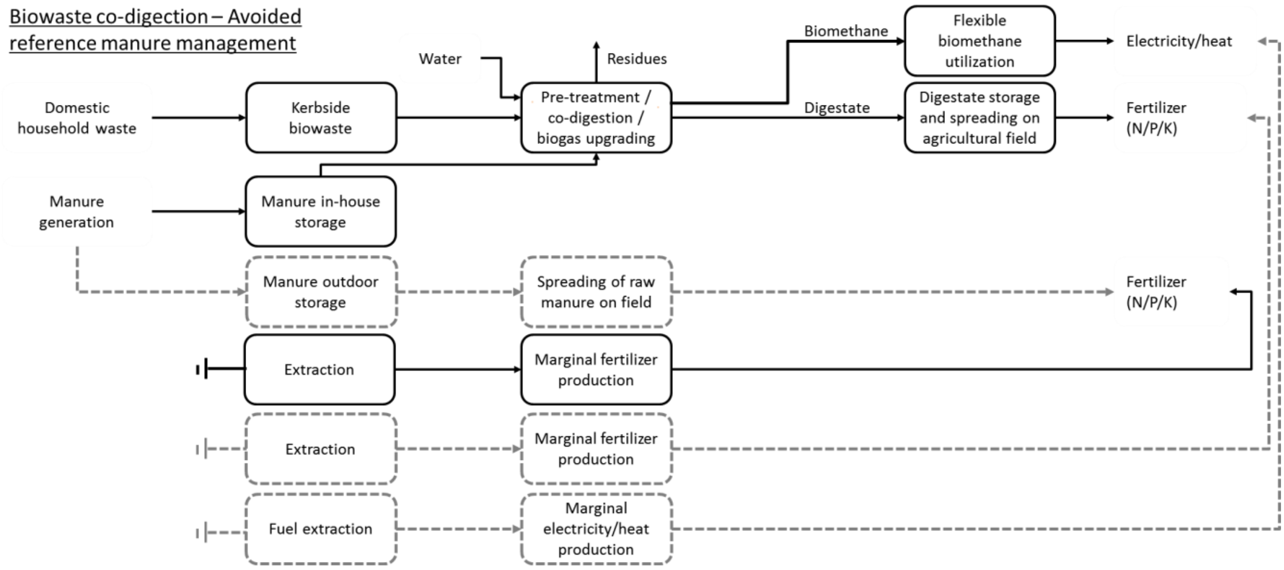


Figure 13: PFD cut-out illustrating co-digestion of biowaste with manure leading to avoided reference manure management; full lines indicate foreground and induced system flows and processes while dotted lines indicate avoided flows and processes (in the background system).

Although the use of energy crops as co-substrates is already being restricted, it is still expected that energy crops may have a role even in long-term. In this study maize was used as a representative of energy crops. Thus, the burdens and benefits of use of biowaste as a co-substrate were weighted against the use of maize, which is associated with both direct and indirect land use changes. The substitution ratio between biowaste and maize was based on methane yield.

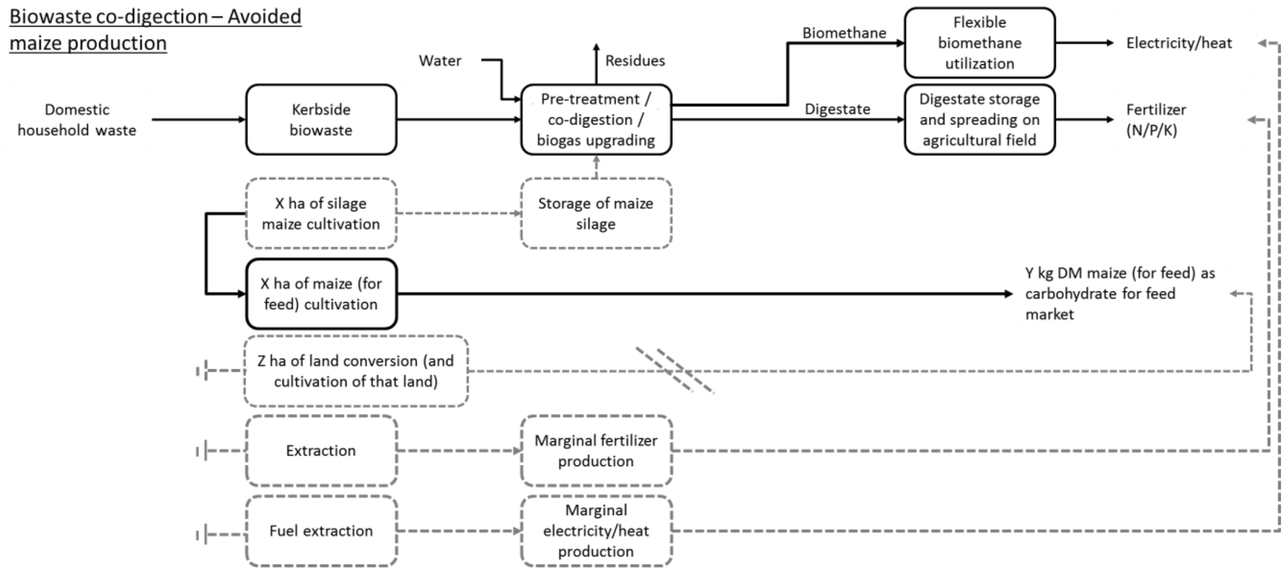


Figure 14: PFD cut-out illustrating co-digestion of biowaste with manure leading to avoided production of maize; full lines indicate foreground and induced system flows and processes while dotted lines indicate avoided flows and processes (in the background system).

2.1.5.4 *Cascading effects – Combustible waste imports*

Under the assumption that the reference waste management system in the region is functioning under stable conditions (current infrastructure is fully utilized), any diversion of waste towards recycling, by increased source separation, or processing of residual waste in central sorting facilities, would liberate combustion capacity in the WtE plants in the system. This in turn, induces a "demand" for combustible waste at the waste incineration plants, or rather a capacity to receive more waste at a given market based gate fee.

Cimpan et al. (2015) identified combustible waste import from countries which still landfill large shares of MSW, as the most probable response to a released WtE capacity in Denmark. In this study, cascading effects were included in connection with the Present (2012-2020) and the Mid-term time period (2020-2035).

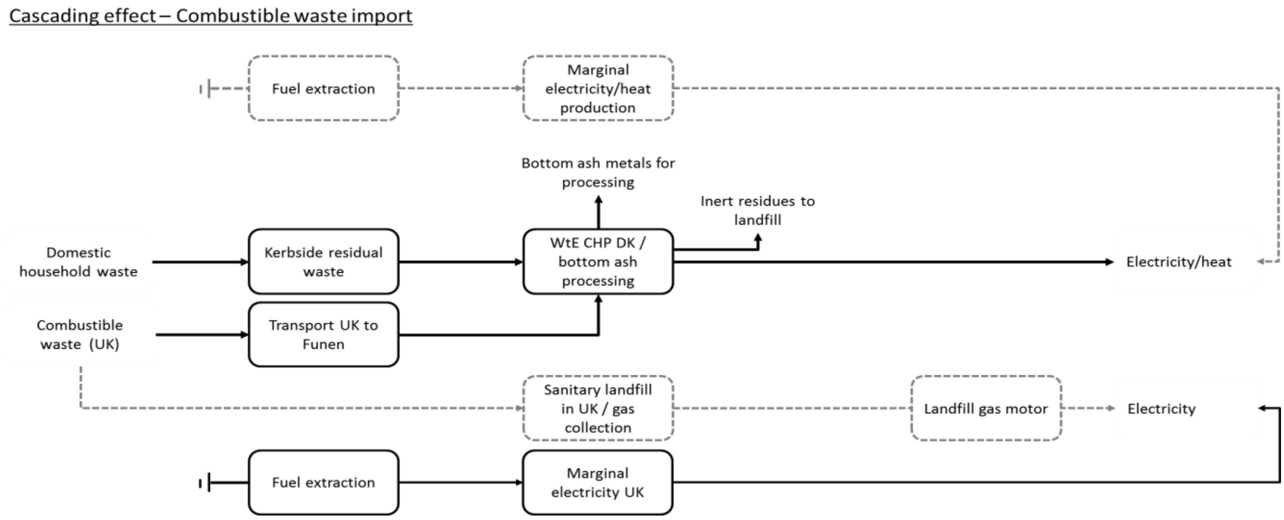


Figure 15: Process flow diagram cut-out illustrating effects pertaining to waste import; full lines indicate foreground and induced system flows and processes while dotted lines indicate avoided flows and processes (in the background system).

Cascading effects were modelled effectively as preparation of combustible waste for export in the UK (here UK is used as a representative for a country which still landfills MSW), sea and land transport to Funen, and combustion in Funish incineration facilities. The GHG impact of these operations was essentially measured against the benefits of electricity and heat production from imported waste in DK and the avoided reference management of combustible waste in the UK. In order to capture a possible range in efficiency (and therefore environmental effects) related to management of combustible, two options have been modelled:

(1) Combustible waste is landfilled in an sanitary landfill with high gas collection and utilization in a gas motor with recovery of electricity;
(2) Combustible waste is landfilled in a sanitary landfill with average gas collection, followed by flaring of the collected gas.

The two options were modelled as described in Cimpan et al. (2015). Imported waste quantities were calculated based on missing (diverted) energy input to the three incineration plants in the system, in every system variant.

2.1.5.5 *Marginal biomass for future energy production*

Biomass marginals are used in the construction of mid-term, long-term and beyond 2050 energy mixes and electricity and heat marginals. The model allows using different biomass marginals. The carbon footprint factors used in this work are presented in table 10, and are taken from Wenzel at al. (2014).

In terms of marginal biomass, two different perspectives have been considered:

(1) A ***progressive biomass marginal***, which reflects an increasing demand for biomass over time. In this perspective the marginal is forest thinning in the Present and Mid-term time perspectives, plantation on high C-stock savannah in Long-time and harvest from existing tropical forests in the Beyond 2050 time prespective.

(2) A ***"dirty" biomass marginal***, which reflects the use of biomass with a high carbon footprint in all four time perspectives, namely harvest from existing boreal forests.

Table 10: Carbon footprint factors for the biomass marginal used in the four time perspectives

	Progressive biomass marginal		**Dirty biomass marginal**	
	100 years amortisation (kg CO_2 per MJ)	20 years amortisation (kg CO_2 per MJ)	100 years amortisation (kg CO_2 per MJ)	20 years amortisation (kg CO_2 per MJ)
Present (2012-2020)	0	0	0.074	0.153
Mid-term (2020-2035)	0	0	0.074	0.153
Long-term (2035-2050)	0.009	0.043	0.074	0.153
Beyond 2050	0.041	0.123	0.074	0.153

Reprocessing waste paper and cardboard into secondary pulp leads to a reduction in use of primary paper pulp. The biomass marginal used for primary pulp production, and thus avoided, was considered coming from "tropical plantations on forest land", in accordance with Reinhard et al. (2010).

2.1.6 Life cycle inventory

2.1.6.1 *Waste stream characterization*

The composition and characteristics of the generated domestic waste, i.e. the functional unit, were compiled as follows:

- The detailed waste flow information collected from each municipality were compiled and aggregated to reflect total flows in the region;
- The composition of the residual domestic waste flow has been described with the help of literature data, in this case by using the detailed characterization of Danish waste from Petersen and Domela (2003), reflecting differences between single-family and multi-family residences;
- The residential ratio calculated for the region (Part 1), together with the weekly generation rates found in Pedersen and Domela (2003), were used to determine the overall waste generated that can be attributed to the two types of residences (Table 11);
- Finally, chemical characteristics were associated to each waste fraction, by using data from Riber et al. (2009) (
- Table 12,
- Table 13).

Table 11: Total waste generated and allocation to single-family (SF) and multi-family (MF) residences

	Total generated		**Total generated SF**		**Total generated MF**	
	tonne/year	wt-%	tonne/year	wt-%	tonne/year	wt-%
Bio-fraction	58,095	37 %	45,669	38 %	12,426	34 %
Paper fraction	34,485	22 %	26,337	22 %	8,148	23 %
Cardboard fraction	12,782	8 %	9,908	8 %	2,874	8 %
Beverage carton fraction	2,599	2 %	2,081	2 %	517	1 %
Foil plastic fraction	6,544	4 %	4,826	4 %	1,718	5 %
Hard plastic fraction	6,977	4 %	5,567	5 %	1,410	4 %
Glass fraction	11,187	7 %	8,571	7 %	2,616	7 %
Fe-metals fraction	4,763	3 %	3,699	3 %	1,064	3 %
Al fraction	1,699	1 %	1,319	1 %	380	1 %
Heavy metal fraction	376	0 %	293	0 %	84	0 %
Rest fraction	17,501	11 %	12,590	10 %	4,912	14 %
Total	**157,007**	**100 %**	**120,860**	**100 %**	**36,147**	**100 %**

Table 12: Chemical characteristics for waste fractions generated in single-family residences

	LHV (MJ/kg ww)	**H2O (% ww)**	**TS (% ww)**	**VS (% ww)**	**C-bio (% ww)**	**C-fossil (% ww)**	**Ash (% ww)**	**N (% ww)**	**P (% ww)**	**K (% ww)**
Bio-fraction	4.33	68.65	31.35	28.54	15.21	0.19	2.80	0.99	0.14	0.30
Paper	12.59	9.51	90.49	72.90	34.90	0.17	17.59	0.17	0.01	0.06
Cardboard	13.84	19.14	80.86	74.15	30.66	6.40	6.71	0.18	0.02	0.04
Beverage carton	17.83	16.64	83.36	80.75	28.25	15.21	2.61	0.30	0.02	0.04
Foil plastic	34.07	14.10	85.90	82.12	0.35	70.09	3.78	0.17	0.02	0.06
Hard plastic	29.97	7.29	92.71	86.93	0.89	65.47	5.77	0.70	0.42	0.10
Glass	-0.17	7.16	92.84	0.00	0.00	0.00	92.84	0.00	0.56	0.00
Fe-metals	-0.26	10.61	89.39	0.00	0.00	0.00	89.39	0.00	0.02	0.03
Aluminium	2.69	14.11	85.89	10.74	6.76	0.07	75.15	0.18	0.03	0.06
Heavy NF-metals	-0.26	10.61	89.39	0.00	0.00	0.00	89.39	0.00	0.02	0.03
Rest	10.59	25.35	74.65	48.86	21.42	6.73	25.79	0.79	0.07	0.37

Table 13: Chemical characteristics for waste fractions generated in multi-family residences

	LHV (MJ/kg ww)	**H2O (% ww)**	**TS (% ww)**	**VS (% ww)**	**C-bio (% ww)**	**C-fossil (% ww)**	**Ash (% ww)**	**N (% ww)**	**P (% ww)**	**K (% ww)**
Bio-fraction	4.46	68.47	31.53	29.08	15.39	0.18	2.46	1.00	0.14	0.28
Paper	12.59	9.51	90.49	72.90	34.90	0.17	17.58	0.17	0.01	0.06
Cardboard	13.17	19.58	80.42	72.62	31.12	4.71	7.80	0.17	0.02	0.04
Beverage carton	17.83	16.64	83.36	80.76	28.25	15.21	2.60	0.30	0.02	0.04
Foil plastic	34.07	14.10	85.90	82.12	0.35	70.09	3.78	0.17	0.02	0.06
Hard plastic	29.98	7.30	92.70	86.88	0.92	65.44	5.82	0.71	0.42	0.10
Glass	-0.18	7.24	92.76	0.00	0.00	0.00	92.76	0.00	0.56	0.00
Fe-metals	-0.26	10.61	89.39	0.00	0.00	0.00	89.39	0.00	0.02	0.03
Aluminium	2.69	14.10	85.90	10.71	6.75	0.07	75.19	0.18	0.03	0.06
Heavy NF-metals	-0.26	10.61	89.39	0.00	0.00	0.00	89.39	0.00	0.02	0.03
Rest	10.33	28.38	71.62	47.39	21.37	6.31	24.23	0.77	0.06	0.35

2.1.6.2 Source separation efficiencies

In systems 3, 4 and 5, the source separation efficiency of citizens in the new Dual-stream kerbside collection scheme has been estimated using existing knowledge from Danish and Swedish studies, such as Dahlen and Lagerkvist (2010), Dahlén et al. (2007), Dansk Affald (2014), Møller et al. (2013).

Table 14: Source separation efficiencies for the Dual-stream and Biowaste

	Bio-fraction	Paper	Cardboard	Foil plastics	Hard plastics	Glass	Fe-metals	NF-metals
Multi-family	50 %	80 %	60 %	40 %	40 %	80 %	50 %	60 %
Single-family	60 %	90 %	70 %	50 %	50 %	90 %	60 %	70 %

2.1.6.3 Collection and transport

Collection and transport are an important source GHGs, it is therefore important to account such operations throughout the systems. In this study, as far as possible, all transport operations between the different points/processes in the systems have been included. These include: (1) waste collection, (2) personal transport to recycling centres, (3) waste transfer to the first treatment operation, (4) long-distance transport of outputs from treatment to final reprocessing, WtE or disposal.

Collection of kerbside material includes diesel consumption used through start, collection at the households and delivery at the treatment facility. The fuel consumption related to kerbside collection of residual waste (and bio-waste) has been estimated as 7.3 L/tonne based on the information provided by the municipalities and haulers (weighted average). Compared to existing studies (Larsen et al., 2009) this is slightly high, but this is probably due to the fact that start and stop is included here, as well as the fact that the waste is not always transferred to larger trucks, resulting in longer distance of transport in low fuel efficient trucks, which would increase fuel consumption per tonne.

The fuel consumption related to collecting recyclables was estimated based on data collected from the municipalities, resulting in 13.9 L/tonne. Collection of paper only (paper/card) was based on data from Odense and resulted in a fuel consumption of 4.9 L/tonne. Fuel consumption in cube collection has been calculated based on collected information resulting in 9.0 L/tonne. Finally, collection of the Dual-stream (including transport to Vojens for sorting) was based on data from Assens municipality, resulting in 13 L/tonne.

Private transport to the recycling centres has also been included based on estimations from Sønderborg municipality, 5.6 L/tonne (Cimpan et al., 2015). This takes into account that 50 % of the trip will be dedicated to visit the recycling centre. Other transportation processes applied in this study is based on long-haul trucks with a diesel consumption of 0.22 L/tkm (Larsen et al., 2009) and ship with a diesel consumption of 0.0104 L/tkm (Operation, barge tanker – Ecoinvent 3 database).

2.1.6.4 Sorting plants

Energy consumption and process efficiencies for plants across the processing chain are summarized in Table 15.

Table 15: Sorting operations

	Recovery efficiency [%]	Electricity [kWh/tonne]	Diesel [L/tonne]	Source
Paper/cardboard quality check	98 %	30	0.5	Merrild et al. (2009)
Glass sorting	98 %	17		Ribe Flaskecentral
Mixed metal sorting	98 % Fe 95 % NF-concentrate	50	2.5	Damgaard et al. (2009)
Heavy media separation	98 % aluminium 95 % heavy NF	80	0.5	Wens et al. (2010)
Mixed plastic sorting	90 % of PP, PE, PET, PS	100		Christiani (2009)
Dual-stream manual sorting (paper, cardboard and foil plastics)	98 % paper 98 % cardboard 95 % foil plastics	10	2	Dansk Affald A/S (2013)
Dual-stream mechanical sorting (metals, plastics and glass)	99 % Fe-metals 95 % NF-concentrate 90 % glass 90 % mixed plastics	30	2	Dansk Affald A/S(2013)

2.1.6.5 Anaerobic digestion and digestate management

Biowaste pre-treatment

This processed was based on the Ecogi technology developed by KomTek Miljø A/S. The waste is pulped with cold water, whereby the dry matter content is diluted from 40 % to 20 %. A biopulp (7-9 % DM) is extracted from the separation tank. The reject is washed and the water is recirculated. The biopulp is concentrated using a screw press, whereby a DM content of 13-22 % is reached (Lorentzen et al., 2013). The biopulp is considered to have a CH_4 yield of 350 Nm^3 per tonne of volatile solids (VS) (Davidsson et al., 2007). Resource consumption amounts to 30 kWh of electricity and 0.5 L of diesel per tonne of bio-waste input.

Table 16: Transfer coefficients in the pulping process

Fraction	To bioslurry (%ww)	To reject (%ww)
Bio	93 %	7 %
Paper	93 %	7 %
Cardboard	93 %	7 %
Beverage carton	75 %	25 %
Foil plastic	1 %	99 %
Hard plastic	1 %	99 %
Glass	1 %	99 %
Fe-metals	1 %	99 %
Aluminium	1 %	99 %
Heavy NF metal	1 %	99 %
Rest	20 %	80 %

Mono-digestion and co-digestion with manure (avoided reference manure management)
Mono-digestion of the biowaste from separate collection and co-digestion of biowaste with manure (pig slurry) was modelled considering the system described in Hamelin et al. (2014) and Hamelin et al. (2011), i.e. a completely stirred main digester operated under mesophilic conditions, equipped with a post digester from which ca. 10% additional methane is captured. The produced biogas is assumed to consist of 65 % CH_4 and 35 % CO_2, with a density of 1.158 kg/Nm^3 biogas. In the case of co-digestion, it was calculated that the systems, on average, allow for the use of manure in a ratio of 60:40 with biowaste. This was determined on the basis of obtaining an input mixture having 10 % of dry matter after the first digestion step (Hamelin et al., 2011, 2014) and a C:N ratio between 10 and 30. The CH_4 yield considered for manure was 319 Nm^3 per tonne volatile solids (VS).

Avoided reference manure management, i.e. storage and field application, was modelled according to Hamelin et al. (2014).

Co-digestion with manure – avoided maize production
Maize silage has been chosen as the energy crop to represent this scenario given its high yield and its high C turnover efficiency. In this study the burdens associate with maize production are avoided by using biowaste in co-digestion with manure instead.

Maize is considered to be produced in Denmark specifically for anaerobic digestion, and as such is displacing another crop, which is here considered to be maize for animal feed. Based on this, the additional hectares of maize needed for anaerobic co-digestion were modelled to displace hectares of maize used for feed. As the production of maize (for energy) instead of maize (for feed), which represents the direct land use changes (DLUC) involved in this study, was assumed to result in negligible changes in emissions, the DLUC was excluded from the model based on the consequential LCA logic. The drop in supply of Danish feed maize resulting from this displacement will cause a relative increase in agricultural prices, which then provide incentives to increase the production elsewhere. Such increased crop production may stem from both increased yield and land conversion to cropland, the latter being also referred to as indirect land use changes (ILUC). This study included the environmental impacts of the latter only. Maize was considered to have a CH_4 yield of 382 Nm^3 per tonne VS. ILUC was modelled as described in (Tonini et al., 2012), and resulted in an emission of 357 t CO_2 eq. per ha feed maize displaced which was annualized over 20 y (i.e. to an annual figure of 18 t CO_2 eq. ha^{-1} displaced y^{-1}).

Digestate and nutrients
When digestate from biogas production is applied to soil, less mineral fertilizer is necessary to be applied. In this model, it was assumed that the nutrients in the digestate replace a quantity of mineral fertilizers equivalent to 40 % for nitrogen, 90 % for phosphorus and 90 % for potassium. The same parameters were used in the case of raw manure application to soil and in the case of digestate from maize.

Leftover carbon in the digestate was in all cases modelled as 90% released in the form of CO_2 within 100 years. Thus 10% carbon storage was included.

2.1.6.6 Incineration WtE and ash processing
In this study waste incineration plants are applied on residue waste streams. In the reference system three different waste incinerators are used in recovering energy from the kerbside collected residual waste;

Odense Kraftvarmeværk A/S, Svendborg Kraftvarme A/S and Energnist[7]. For the alternative systems only Odense CHP will be applied in energy recovery of the RDF.

Residue streams from pre-sorting of paper, cardboard and glass will be incinerated in Odense as well, assuming it is sorted at Marius Pedersen A/S and therefore locally disposed of. The dual-stream sorting will happen at Dansk Affalds plant in Vojens, Denmark, from which the residues will be sent for incineration at Haderslev Kraftvarmeværk (Elsam A/S). The residues related to plastics and NF-concentrates (from central sorting) sent for specialized treatment outside Denmark will be incinerated using efficiencies of an average European waste incinerator.

Table 17: Electricity and heat recovery in incineration facilities

	Odense CHP*	Svendborg CHP**	Kolding CHP***	Haderslev CHP****	Avg. EU CHP*****
Heat	64.1 %	71.9 %	69.2 %	49.0 %	45.9 %
Electricity	20.4 %	11.4 %	8.5 %	16.0 %	14.2 %

**According to green account of Odense Kraftvarmeværk A/S 2013 (Vattenfall, 2013)*

***According to yearly report from Svendborg Kraftvarmeværk A/S 2013 (Svendborg Kraftvarmeværk, 2014)*

****According to green account from Trekantsområdets Affaldsselskab I/S 2013, average for both lines combined (TAS, 2014)*

*****According to green account from Haderslev Kraftvarmeværk 2012 (DONG, 2012)*

******Average European: CEWEP (Reimann, 2009).*

The main residue output, bottom ash, is typically stored for several months (the process is called ageing) to improve leaching properties, before it is processed to recover metals. An oxidation coefficient of 20 % was used in the model in order to account for significant shares of metals which become unavailable for recovery after the incineration process due to partial volatilization and surface oxidation (Biganzoli et al., 2012) and during the ageing process (Vries et al., 2009). State-of-the-art mechanical-based sorting in Denmark achieves around 80% ferrous metals (Fe) recovery and 60% non-ferrous (NF) recovery (of metals present in metallic form) (Allegrini et al., 2014).

2.1.6.7 Central sorting

In this study Central Sorting is an alternative to direct incineration of residual waste from households. Central sorting takes place in high capacity facility (100,000-120,000 tonnes/year), which can be divided roughly into two sections: (1) mechanical pre-processing and automated material sorting, and (2) processing of organics. The latter section consists, depending on the system variant, of different processes which are described in the sections below.

[7] Formerly known as Trekantsområdets Affaldsselskab I/S (TAS), Kolding

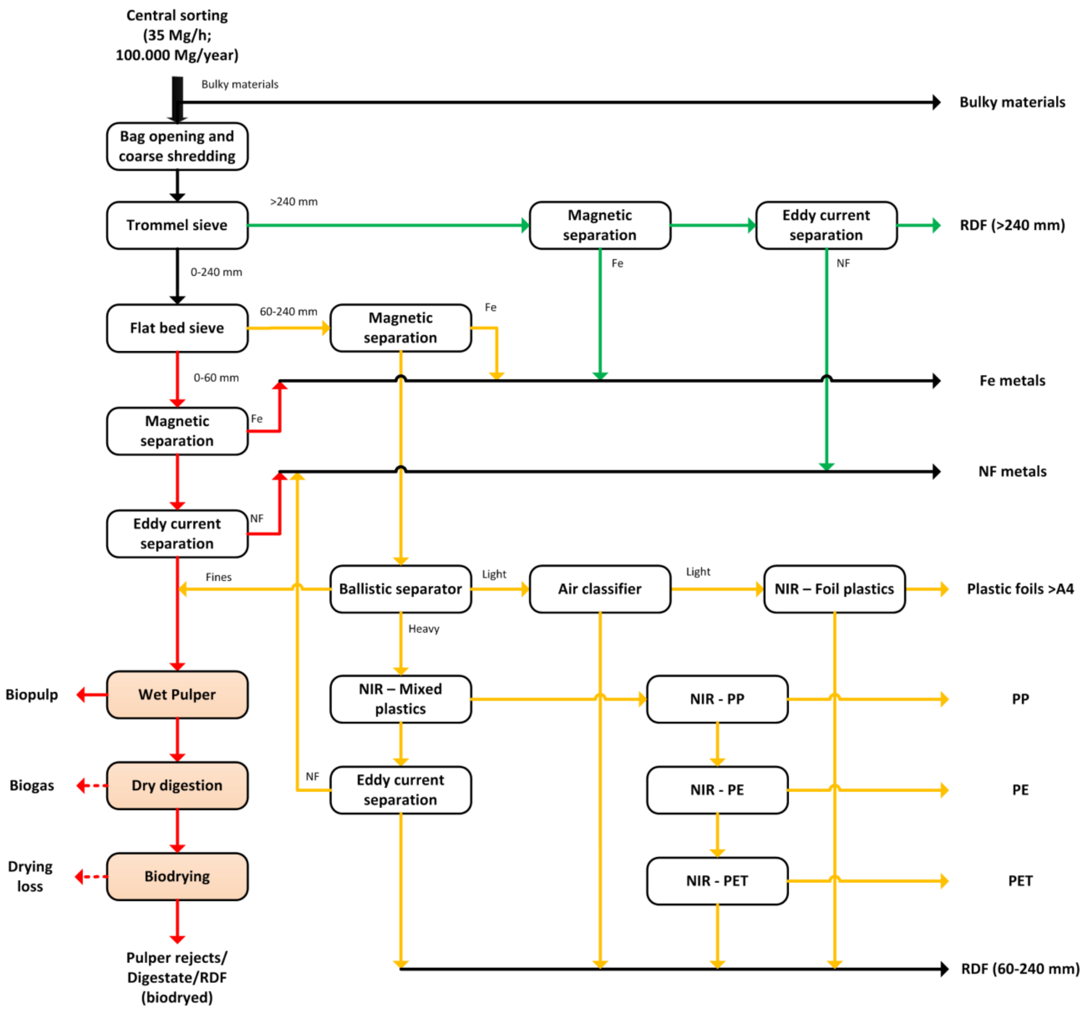


Figure 16: Process flow diagram for the residual waste Central Sorting plant. Colour coding: green flows – oversize line, yellow flows – middle line, and red flows – fines line.

Mechanical pre-processing and automated material sorting

The pre-processing section consists of bag opening and sieving in trommel and flatbed sieves. Following size fractionation through sieving, the input waste is now split into size intervals: >240 mm, 80-240 mm and <80 mm. The three streams are then processed individually downstream. The material directed to the middle line is also pre-conditioned by air classification and ballistic separation before sorting. Sorting is based on standard technologies using, magnetic separators for ferrous metals, eddy current separators for non-ferrous metals and near-infrared (NIR) sorters for plastics (both hard plastics and foil plastics). The organics separation is achieved by mechanical concentration in a fine material stream following the initial sieving steps. The concentrated organics are then fed to the next section of the plant.

Biopulp production and biogas production

In the system variants including this option of processing organics from CS, the concentrated stream from mechanical processing is fed to a wet pulping process. This process is the same used for pre-treatment of biowaste from separate collection. The technology is assumed to function with the same efficiency in the case of both types of input, due to the composition displayed, which in both cases is characterized by around 10 % contamination (non-biodegradable materials).

The biopulp recovered from the pulper is directed to biogas production. The biogas plant can be part of the Central sorting complex or a separate plant. Digestion was modelled on the same principles as biowaste digestion.

Dry digestion

Dry or high-solids digestion is anaerobic digestion performed with waste having TS content between 20 % and 50 %. Existing technologies are well suited for heterogeneous waste streams and do not require intensive pre-treatment.

The process modelled in this study is based on the BEKON process, which used gas-proof box-shaped reactors, operated in batch mode at mesophilic temperatures (BEKON, 2015). The biomass intended to be digested is mixed on a 50:50 ratio with substrate that has already been digested (this serves as inoculum) and fed via front-end loader into the reactors. The substrate remains in the digester for a period of approx. 4-5 weeks, however if subsequent digester cycles are considered the total retention time is approx. 8-10 weeks. Once the material is inside the reactors no further mixing is required, however, excess cell fluid (percolation liquid) discharged during the fermentation process is collected by a drainage system and returned to the digesting material in a cycle to keep it moist. Wall and floor heating is used to keep the temperature of the microorganisms constant.

Consumption of electricity has been measured to be 2-3 % of potential electricity production from the biogas produced (Karagiannidis et al., 2008). The digestion of the concentrated organics was assumed to have a CH4 yield of 290 Nm^3 per tonne VS.

Biological drying

Biological drying or biodrying is a variation of aerobic decomposition (composting) performed in closed reactors, whereby the biological heat produced by microorganisms in the initial stages of decomposition is harnessed and augmented by intense forced aeration which facilitates the fast removal of moisture by convective evaporation (Velis et al., 2009). Many commercial scale technology providers exist. The process runs between 5 and 15 days (batch-wise), depending on the technology provider.

In contrast to classical composting processes, which aim at maximum degradation, the objective in biodrying is the fast removal of moisture, with minimum substrate degradation, until biological activity stops (15-20^oC), rendering the output material storable for short-term (Grüneklee, 2002).

In this study, the process was modelled based on Herhof technology. The substrate is biodried within air- and liquid-tight box reactors, with capacity of 600 m^3. Filling/unloading and handling of the box lid can be done completely automatically by means of cranes. In the different system variants, the lower heating value (LHV) of the concentrated organics stream was increased from 4-5 MJ/kg to 11-13 MJ/kg, while the moisture content was reduced from 60-65 % to around 20 %,. On average, around 40 % of the organic substrate VS was consumed in the process.

2.1.6.8 Material reprocessing and avoided primary production

The management chain for recyclable materials, both from separate collection and recovered in the central sorting facility, consists of refining plants and reprocessing plants. In most cases both operations take place outside the case region. The latest literature was used to model transfers and especially material losses across the management chain.

Secondary materials compete with primary produced materials on commodity markets. At this point quality differences between secondary materials and their virgin counterparts determine the substitution potential of the latter by the former. This is especially significant for fibre-based materials (paper and cardboard) and plastics. The reprocessing yields and substitution ratios used in the model are presented in Table 18 below.

Table 18: GW coefficients for secondary/reprocessing and avoided primary material production incl. reprocessing yield and substitution potentials used in the modelling

		CO_2 eq. [kg/kg]	**Reprocessing yield (%)**	**Substitution ratio (%)**
Paper	secondary	0	81 %	90 %
	primary	1.63		
Cardboard	secondary	0	75 %	95 %
	primary	0.97		
Glass	secondary	0.63	92 %	100 %
	primary	1.42		
FE-metals	secondary	0.48	81 %	100 %
	primary	3.01		
Aluminium	secondary	0.87	82 %	100 %
	primary	16.46		
Heavy NF (Cu)	secondary	2.52	85 %	100 %
	primary	6.50		
Foil plastics	secondary secondary CS	0.99 0.99	75 % 60 %	70 % 70 %
	primary	2.27		
Hard plastics	secondary secondary CS	1.20 1.20	75 % 60 %	80 % 80 %
	primary	2.55		

2.2 Results and discussion

The section contains the results of the mass flow modelling as well as the carbon footprint assessment.

2.2.1 Mass flow modelling results

This part provides information on the mass flow analysis presented through flow charts as well as material and energy recovery in the different modelled systems.

2.2.1.1 Mass flows and functional outputs in the simulated systems

To visualize the systems designed and simulated in this study, process flow diagrams (PFDs) were drawn. In order to represent all the key system variants, PFDs for Systems 0, 2, 3, and 5, including all system variants were made (the PFD for System 0 is shown in Figure 18 and Figure 20, and the PFDs of Systems 2, 3 and 5 are found in the Appendix 1), whereas System 1 and 4 are not represented by process flow diagrams, as the flows in these are ultimately the same as in system 2 and 5, with the only difference being related to the degree of implementation of biowaste collection (SF only or both SF and MF).

In addition, illustrated in this section, are Sankey diagrams for System 0 (Figure 17 and Figure 19). Sankey diagrams are used to give a visualisation of the transfer of mass through a system (mass balance), which constitutes the backbone of any system analysis. This gives an easy overview of the size of the mass flows throughout the systems. Process flow diagrams, on the other hand, give additional information besides mass, such as regarding the functional outputs of the system like energy, secondary materials and organic fertilizer. More importantly process flow diagrams are intended to illustrate the interactions between the foreground system and background system, thus giving a full picture "from cradle to cradle". It is important to state that some of the interactions with the background systems were not included in the process flow diagrams, in order not to agglomerate the drawings. These included the cascading effects leading to waste import for incineration and manure co-digestion, with both possible interactions: (1) avoided reference manure management and (2) avoided maize production.

System 0, in its first variant with WtE (0-WtE) represents the reference, or the existing waste management in the region at the time this study was conducted (Figure 17 and Figure 18). The material flows collected for recycling, under various schemes, in the 10 municipalities are shown aggregated to three main flows, pertaining to their collection, either property close (kerbside) or in public collection points (the cube system and recycling centres). All residual waste collected in the region, amounting to 111,800 tonnes, was transported to three incineration plants as described in Part 1 of this report. In the process flow diagrams, incineration is represented as one process, therefore the input and output flows are an aggregated representation of the three individual plants.

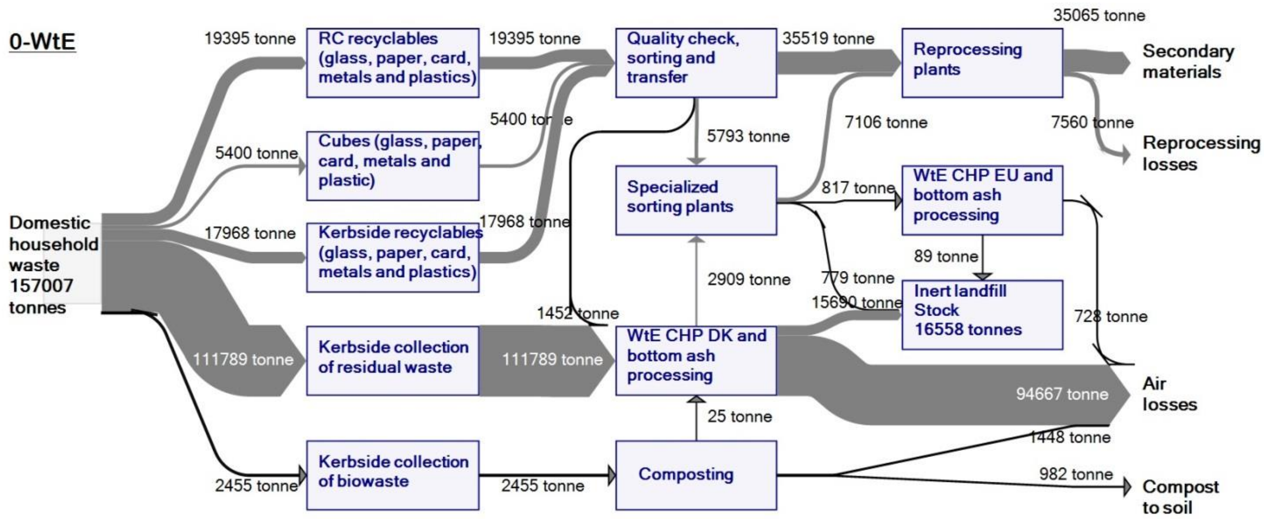


Figure 17: System 0-WtE: mass balance (Sankey diagram)

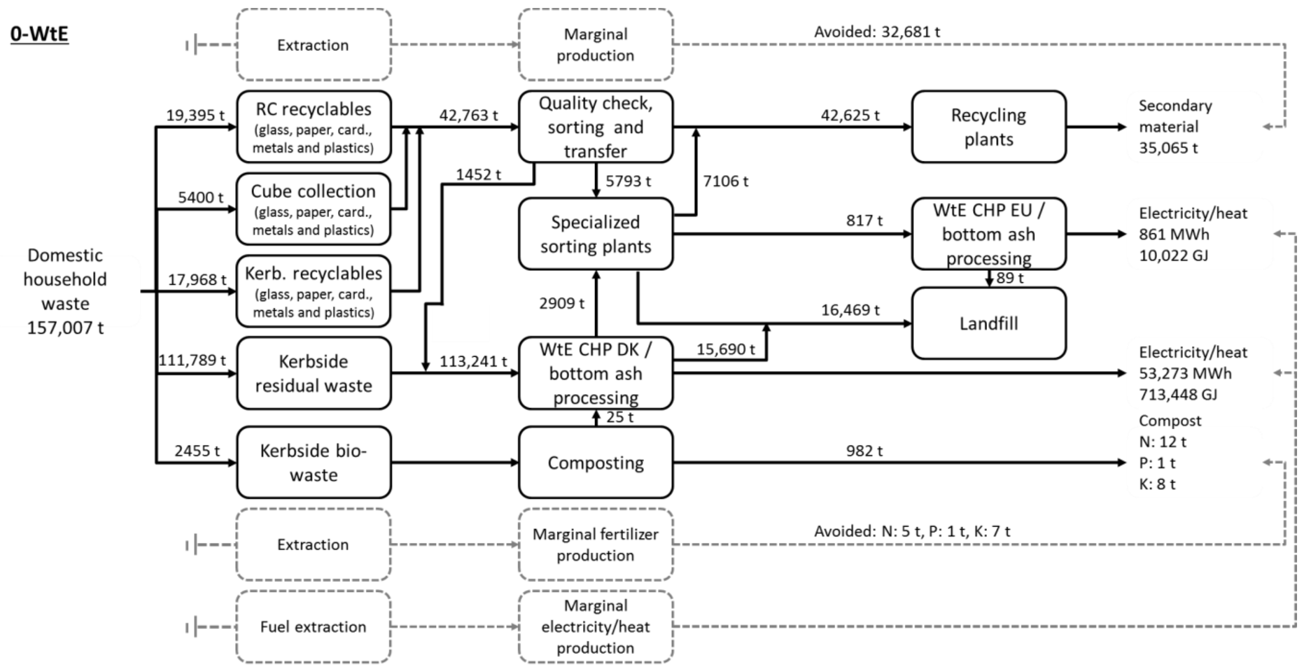


Figure 18: System 0-WtE: process flow diagram; full lines indicate foreground and induced system flows and processes while dotted lines indicate avoided flows and processes (in the background system).

System 0, with central sorting (CS) in its three variants, maintains the existing degrees of separate collection. However, all residual waste collected in the region was modelled as transported and processed in a central sorting facility. In the central sorting facility, metals and plastics (amounting to around 10,000 tonnes/functional unit) are sorted from residual waste, and sent further to refining or recycling plants outside the region. Non-recoverable materials which have a high calorific content are concentrated in RDF streams (45,000 tonnes/functional unit) which can be stored temporarily and used for energy production in the existing incineration facilities (here the Odense incineration plant was modelled). Biodegradable organic fractions (i.e. food waste) are concentrated in a stream (57,000 tonnes/functional unit), the further treatment of which was in this study modelled as three different options. The mass flows and system implications related to the three treatment options are illustrated in Figure 19 and Figure 20.

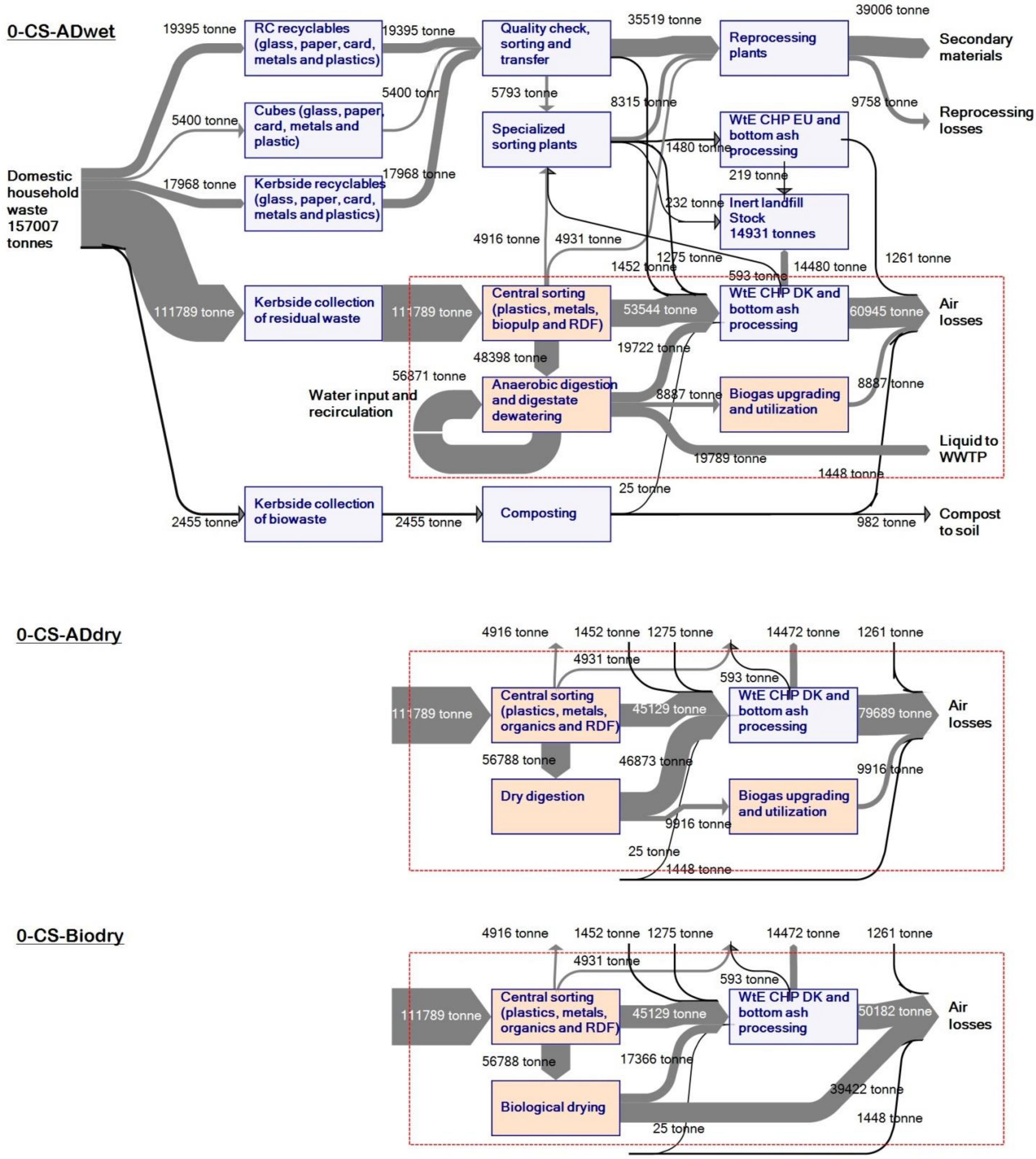


Figure 19: System 0-CS: mass balance (Sankey diagram); coloured processes indicate foreground system changes compared to System 0-WtE.

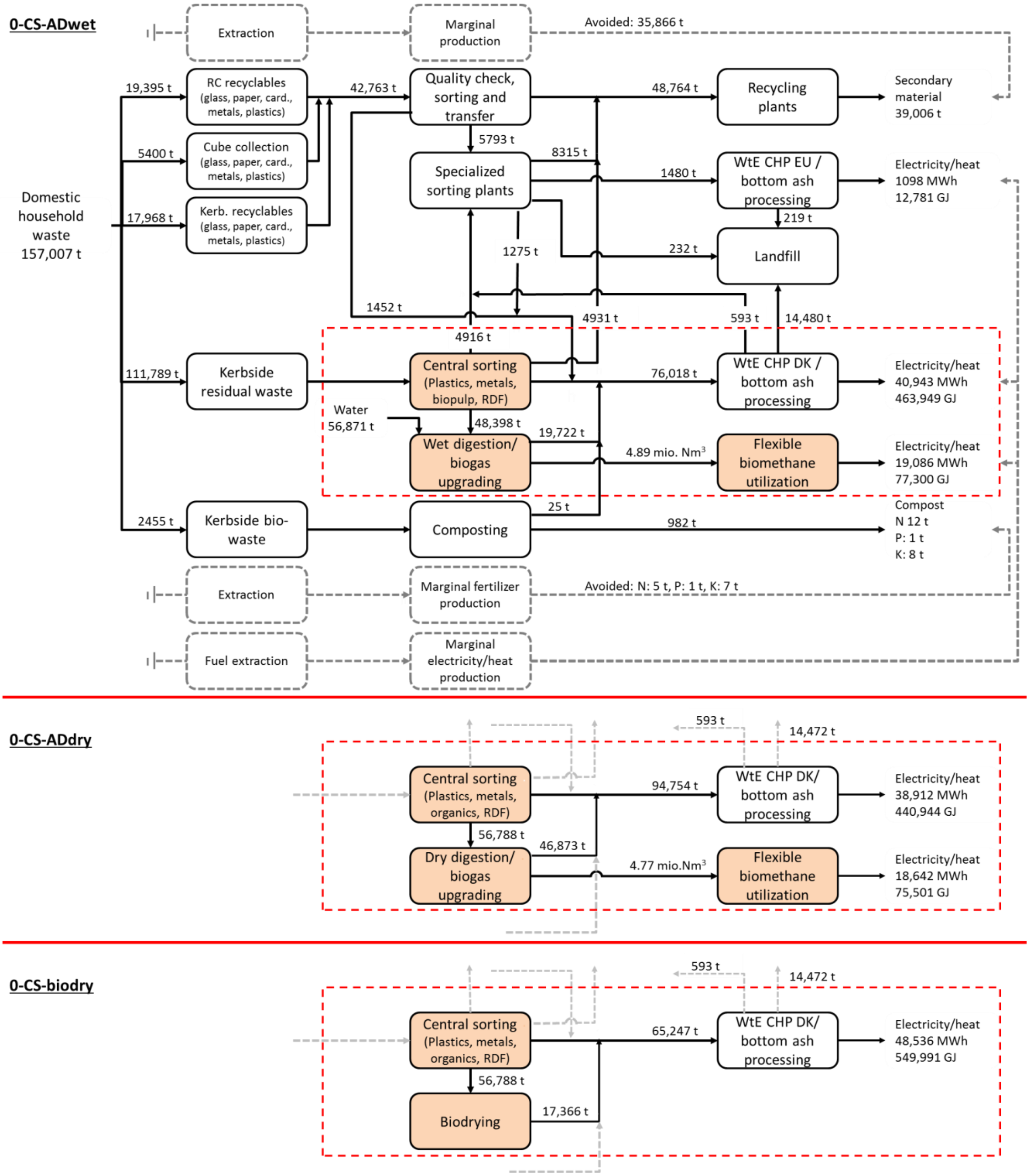


Figure 20: System 0-CS-ADwet/ADdry/Biodry: process flow diagram; full lines indicate foreground and induced system flows and processes while dotted lines indicate avoided flows and processes (in the background system); coloured processes indicate foreground system changes compared to System 0-WtE.

The process flow diagrams for other significant system changes; system 2 (biowaste collection all over), system 3 (dual-stream collection of recyclables) and system 5 (dual-stream and biowaste collection all over) can be found and studied in appendix 1. In general the interaction with the background systems changes from energy production towards material as well as mineral fertilizer production, the more source separation is applied to the systems.

2.2.1.2 *Material recovery – source separation and recycling*

This section is divided into two parts. The first part being related to source separation, including both recyclable material and biowaste, and the second being related to material recovery (excluding biowaste) from all parts of the systems including source separation, central sorting and bottom ash metal recovery.

Source separation

The table below (Table 19a+b) shows results from the mass model, detailing the quantities of waste collected separately in each of the 6 simulated systems. With consideration to the functional unit used in this study, the following can be delineated:

- Approximately 29 % of domestic household waste was collected separately and directed towards recycling or composting in the current waste management system in the region (2013, System 0);
- Implementation of separate collection of biowaste in single-family residences throughout the region was estimated to add another 17 %, increasing the separate collection rate in the region to 46 % (System 1);
- Owing to the relatively small ratio of multi-family residences in the region, their somewhat lower waste generation rate and source separation efficiency, the institution of separate collection of biowaste in multi-family residences throughout the region was estimated to only contribute an additional 4 % increase to the total separate collection (System 2);
- Despite the fact that separate collection of recyclable materials is already relatively high in some municipalities, the homogenous installation of a kerbside commingled scheme (such as DuoFlex) was estimated to have a great impact on the recovery of materials for recycling in the region, leading to a possible increase in total separate collection of 12 % compared to the existing disparate schemes (System 3);
- If separate collection of biowaste is added to the kerbside commingled collection of recyclables, the total separate collection rate was estimated to increase well above 50 % of generated domestic waste; that is 58 % with biowaste collected in single-family residences (System 4) and 63 % when multi-family residences are also included (System 5).

Table 19a: Total separate collection achieved in the simulated systems

	Total generated		**System 0**		**System 1**		**System 2**	
			Separate collection		Separate collection		Separate collection	
Waste fraction	tonne/year	wt.%	tonne/year	wt.%	tonne/year	wt.%	tonne/year	wt.%
Bio-fraction	58,095	37 %	2,430	2 %	27,401	17 %	33,614	21 %
Paper fraction	34,485	22 %	23,173	15 %	23,173	15 %	23,173	15 %
Paper-card fraction	12,782	8 %	4,759	3 %	5,349	3 %	5,490	3 %
Beverage carton fraction	2,599	2 %	0	0 %	0	0 %	0	0 %
Foil plastic fraction	6,544	4 %	298	0 %	298	0 %	334	0 %
Hard plastic fraction	6,977	4 %	2,613	2 %	2,907	2 %	2,978	2 %
Glass fraction	11,187	7 %	7,991	5 %	8,079	5 %	8,115	5 %
Fe-metals fraction	4,763	3 %	2,163	1 %	2,222	1 %	2,236	1 %
Al fraction	1,699	1 %	808	1 %	808	1 %	808	1 %
Heavy metal fraction	376	0 %	154	0 %	154	0 %	154	0 %
Rest	17,501	11 %	829	1 %	1,836	1 %	2,387	2 %
Total	**157,007**	**100 %**	**45,218**	**29 %**	**72,227**	**46 %**	**79,287**	**50 %**

Table 19b: Total separate collection achieved in the simulated systems (continued)

	Total generated		System 3		System 4		System 5	
			Separate collection		Separate collection		Separate collection	
Waste fraction	tonne/year	wt.%	tonne/year	wt.%	tonne/year	wt.%	tonne/year	wt.%
Bio-fraction	58,095	37 %	2,430	2 %	27,401	17 %	33,614	21 %
Paper fraction	34,485	22 %	30,222	19 %	30,222	19 %	30,222	19 %
Paper-card fraction	12,782	8 %	8,660	6 %	9,249	6 %	9,391	6 %
Beverage carton fraction	2,599	2 %	0	0 %	0	0 %	0	0 %
Foil plastic fraction	6,544	4 %	3,100	2 %	3,100	2 %	3,135	2 %
Hard plastic fraction	6,977	4 %	4,052	3 %	4,347	3 %	4,417	3 %
Glass fraction	11,187	7 %	9,806	6 %	9,895	6 %	9,930	6 %
Fe-metals fraction	4,763	3 %	2,751	2 %	2,810	2 %	2,824	2 %
Al fraction	1,699	1 %	1,151	1 %	1,151	1 %	1,151	1 %
Heavy metal fraction	376	0 %	255	0 %	255	0 %	255	0 %
Rest	17,501	11 %	2,117	1 %	3,123	2 %	3,674	2 %
Total	**157,007**	**100 %**	**64,545**	**41 %**	**91,554**	**58 %**	**98,614**	**63 %**

Full system material recovery

The total amount of materials directed towards recycling, as presented in Table 19, is however higher still, if metals recovered from incineration ash or alternatively, metals and plastics recovered in the central sorting plant, are also accounted.

Central sorting will not change the amount of paper, cardboard and glass recovered for recycling, since only metal and plastic concentrates are recovered (and a bio-concentrate). Figure 21 gives an overview of the mass flows throughout the central sorting facility. The input composition of the waste is crucial to the outputs, and since the composition of the residual waste varies among the different degrees of source separation, a generic flow has been presented (not directly representing any system variant). The streams of metals and plastic polymers might seem insignificant compared to the flows of RDF and concentrated organics, and the value of recovering metals and plastics should therefore be put into perspective. Table 20 shows, how much is recovered from the central sorting facility in terms of metals and plastics related to the two system variants, that affects the direction of recyclable material the most significantly; that being system 0 and system 3. System variants including source separation of biowaste only affects the recovery of Fe-metals and plastics from central sorting slightly because of miss-sorting, i.e. some of the plastics and Fe-metals are collected in the bio-bin and the material is not recovered from the reject.

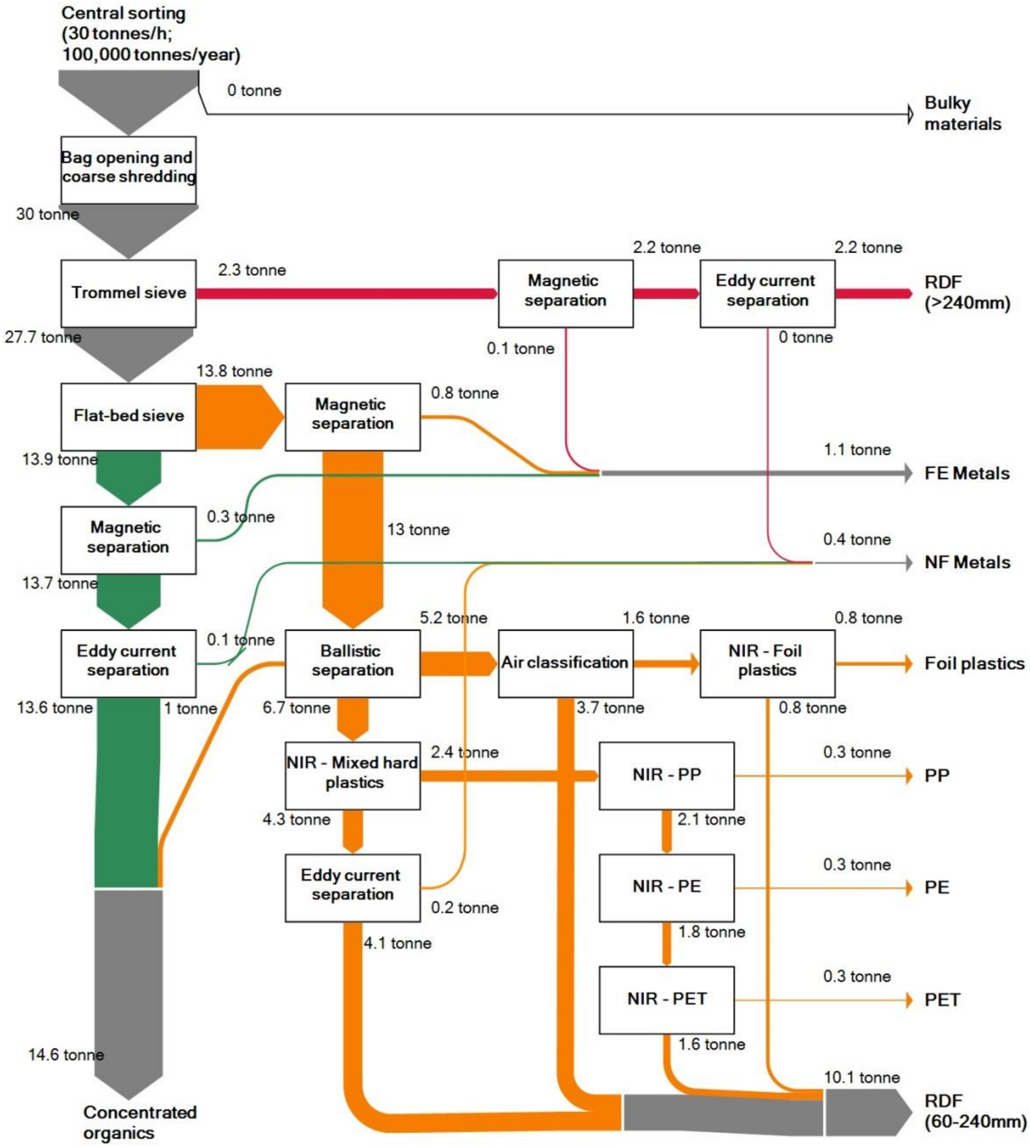


Figure 21: Sankey diagram for the Central Sorting plant, the mechanical processing and automated sorting section (the input composition was generic, thus the size of the flows does not represent accurately any system variant, as the model results are different for each system variant which includes CS).

Direct incineration of the residual waste stream will mean, that the plastics within the stream will be lost. However, it is possible to recover part of the metals from the remaining bottom ashes from the incineration. The metals will be oxidized through the incineration process, and parts of it will be bound to the ash particles, whereby some of the metals will be lost after incineration. Parts of it will though be recovered through bottom ash sorting, and Table 20 gives an overview of, how much is recovered in the two system variants, which affects recovery of recyclables the most (system 0 and system 3). The recovery is presented for both direct incineration of the residual waste and central sorting applied before incineration.

Table 20: Material recovery from bottom ash and central sorting in the 2 main system variants related to recovery of recyclable material i.e. plastics and metals (tonnes/year). Metal fractions represent pure metals, i.e. the metal concentrates from central sorting and bottom ash sorting after further sorting.

Material (tonnes/year)	**System 0**			**System 3**		
	WtE	**CS**		**WtE**	**CS**	
	Bottom ash	Mechanical sorting	Bottom ash	Bottom ash	Mechanical sorting	Bottom ash
Aluminum	419	548	156	285	337	123
Heavy NF metals	105	137	39	63	75	27
Fe-metals	1,682	2,293	241	1,279	1,774	165
Hard plastics		2,188			1,476	
Foil plastics		2,743			1,514	
Total (tonnes/year)	2,206	7,909	437	1,627	5,176	315
Total (% of generated)	1.4	5.0	0.3	1.0	3.3	0.2

Combining source separated material, centrally sorted material and metal recovery from bottom ash, the material recovery for the two significant system changes have been summed and displayed in Figure 22. This displays 4 bar charts for comparison; system 0-WtE, System 0-CS, System 3-WtE and System 3-CS. The systems are compared based on material collection (red bar) of each material fraction relative to the potential (dark blue bar) in the system. The figure also presents the losses through sorting and reprocessing (purple and light blue bar) as well as the substitution ratio (orange bar), i.e. how much virgin material is replaced. Additional to the red bar (separate collection), a light red and a light green bar can be found; these representing recovery from bottom ash and central sorting respectively.

The figure shows how the recovery of paper, cardboard and glass increase, when changing the separate collection from the existing collection system (system 0) to the dual-stream collection (system 3). Additionally comparing 0-WtE with 3-WtE shows, that increasing separate collection will increase recovery of metals and plastics as well. The sorting losses related to hard plastics are though quite significant, since there is a great loss in the sorting of the dual-stream plastic polymers (non-recyclable plastics). Also the significance of recovering metals from bottom ash becomes quite visible, since the source separation is increased by 14 %, whereas the input to reprocessing only increased by 6 %.

Comparing 0-CS with 3-CS show very modest improvements in material recovery (and input to reprocessing) of metals and hard plastics, when having a combination of improved source separation (dual-stream collection) and central sorting, compared to keeping the existing collection scheme, and treating the residual waste through central sorting. This indicates, that in system variants with central sorting applied, improved source separation of recyclables through dual-stream collection will only benefit in terms of paper/cardboard and glass recovery.

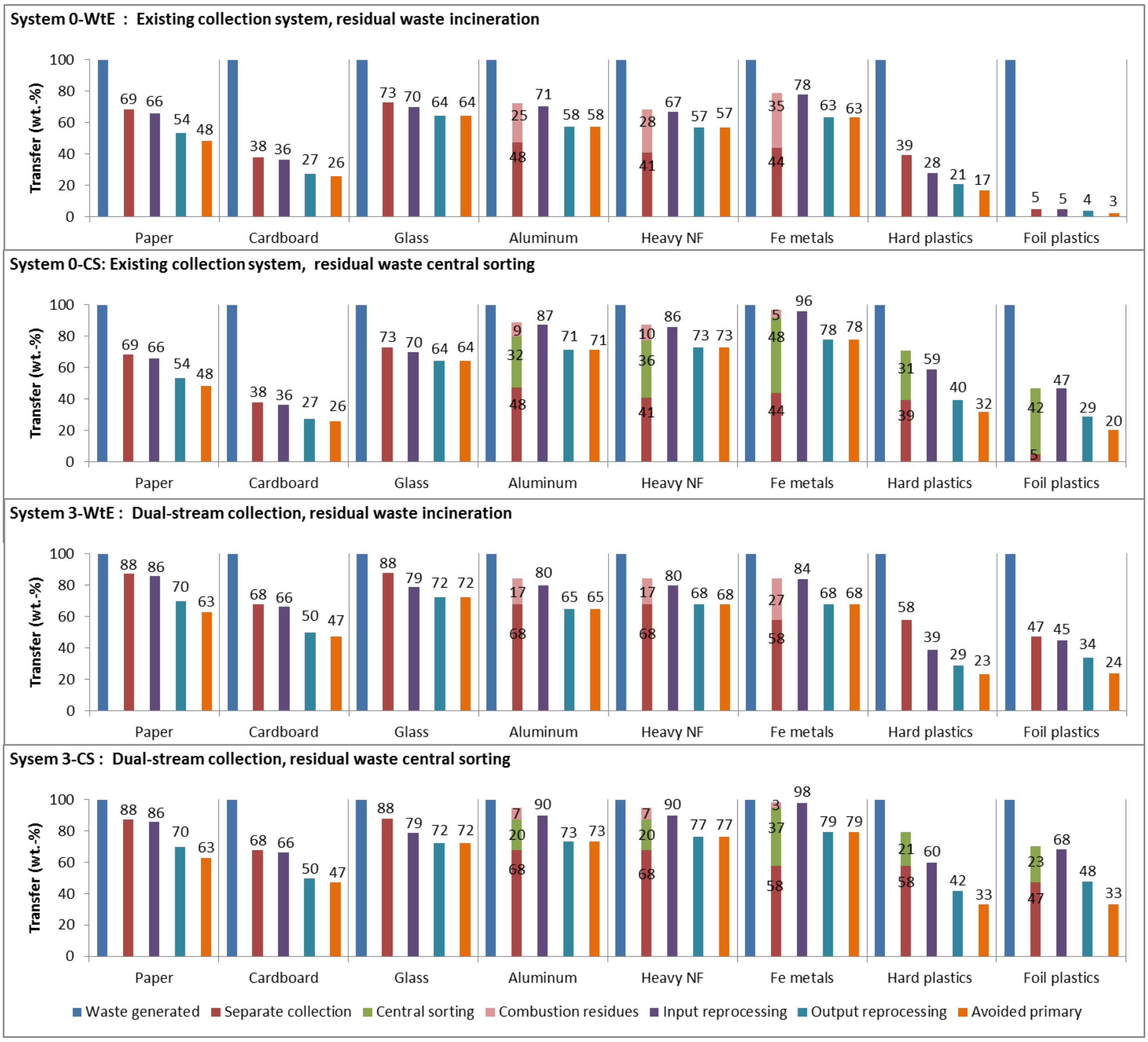


Figure 22: Material recovery efficiency in two main system alternatives including WtE and CS variants

Compared to source separation alone, central separation of metals and plastics will increase the material recovery rate with about 5 %-points in the systems 0, 1 and 2 (i.e. systems having the existing structure of collecting recyclable material) and about 3 %-points in system 3, 4 and 5 (i.e. systems having a dual-stream collection of recyclables).

The centrally recovered bio-concentrate cannot be treated in the same way as source separated biowaste in terms of disposal. Nutrients within the biomass cannot be recirculated (because of peak-load risks of contamination) and the centrally separated biomass will therefore only be utilized for energy purposes.

2.2.1.3 Energy recovery – electricity and heat

Figure 23 below resumes modelling results on energy balances for 24 system variants. These being related to four main system variants: system 0 (existing collection scheme), system 2 (biowaste collection all over), system 3 (dual-stream collection) and system 5 (dual-stream collection and biowaste collection all over) including variations of mono- and co-digestion of source separated biowaste. Figure 23 does not include the additional energy that would be produced from imported waste, due to cascading effects, which is illustrated in Figure 24. Positive values represent production in a system, while negative values sum the total energy consumed in the same system. Colour coding is used to illustrate the "quality" of electricity and heat produced from waste, i.e. purple and blue are used to indicate continuous electricity and heat production, red is an indicator of flexible electricity (from biomethane) and heat (from RDF), and brown indicates system consumption.

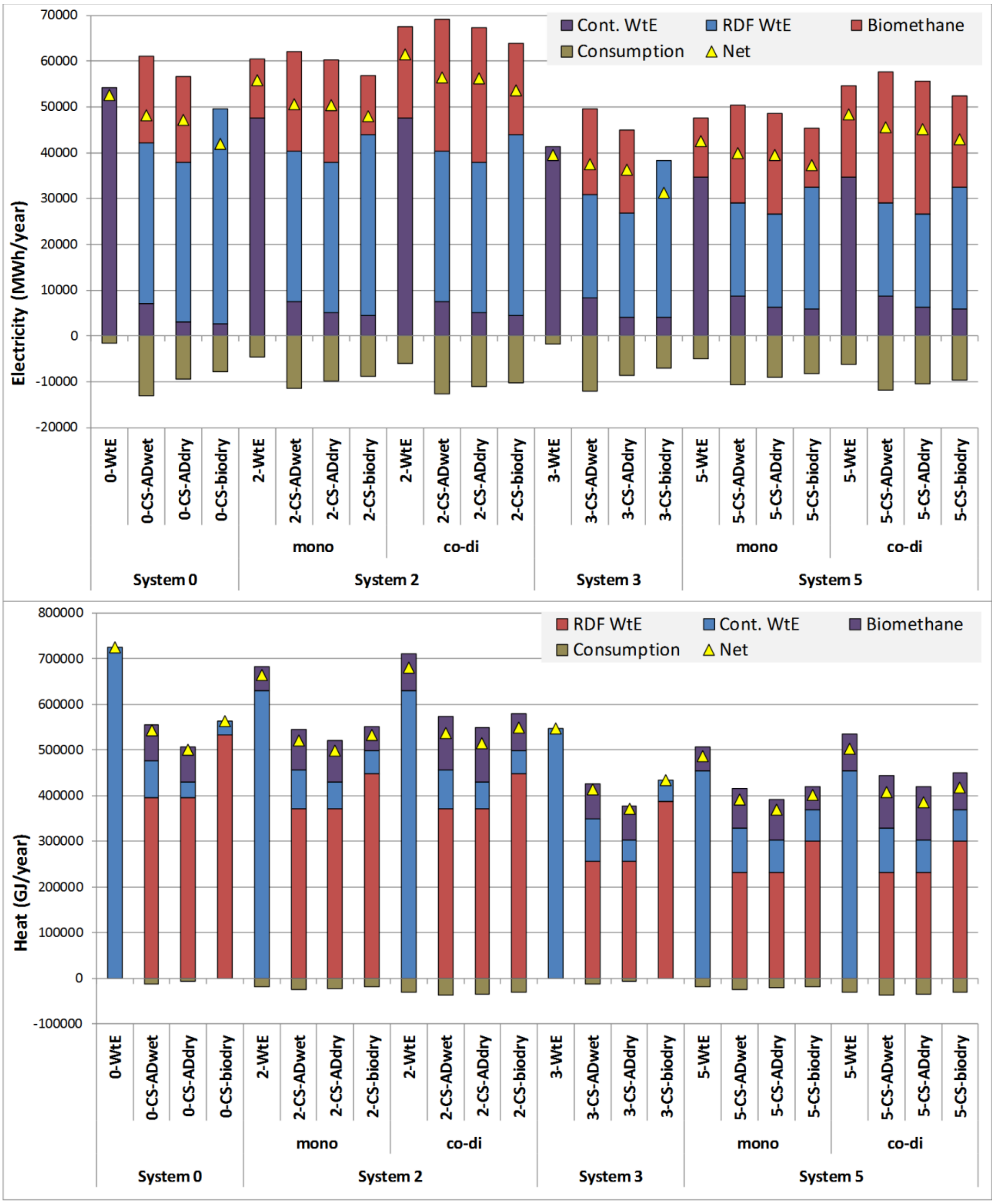


Figure 23: Electricity and heat production (positive values) and consumption (negative values), in 4 main systems, including 8 system variants with mono-digestion and manure co-digestion.

As can be observed, in system variants which include biogas production the total production of electricity was higher than in system variants with only incineration (i.e. 0-WtE, 0-CS-Biodry, 3-WtE and 3-CS-Biodry). However, the same systems (with biogas) produced overall less heat. Own system consumption of electricity was significantly higher in system variants with central sorting. When consumption is accounted in the balance it seems to indicate that all variants with central sorting produce a net output which is smaller than their WtE alternative. The highest net electricity output of all system variants was found for 2-WtE when co-digestion with manure was included (avoiding reference manure management).

Although heat production was lower in all system variants with central sorting, the "quality" of recovered heat is starkly different. The model output indicated that most heat can be produced with flexibility, i.e. from RDF stored temporarily until the cold season. This is expected to overall lead to higher environmental savings despite the lower heat output.

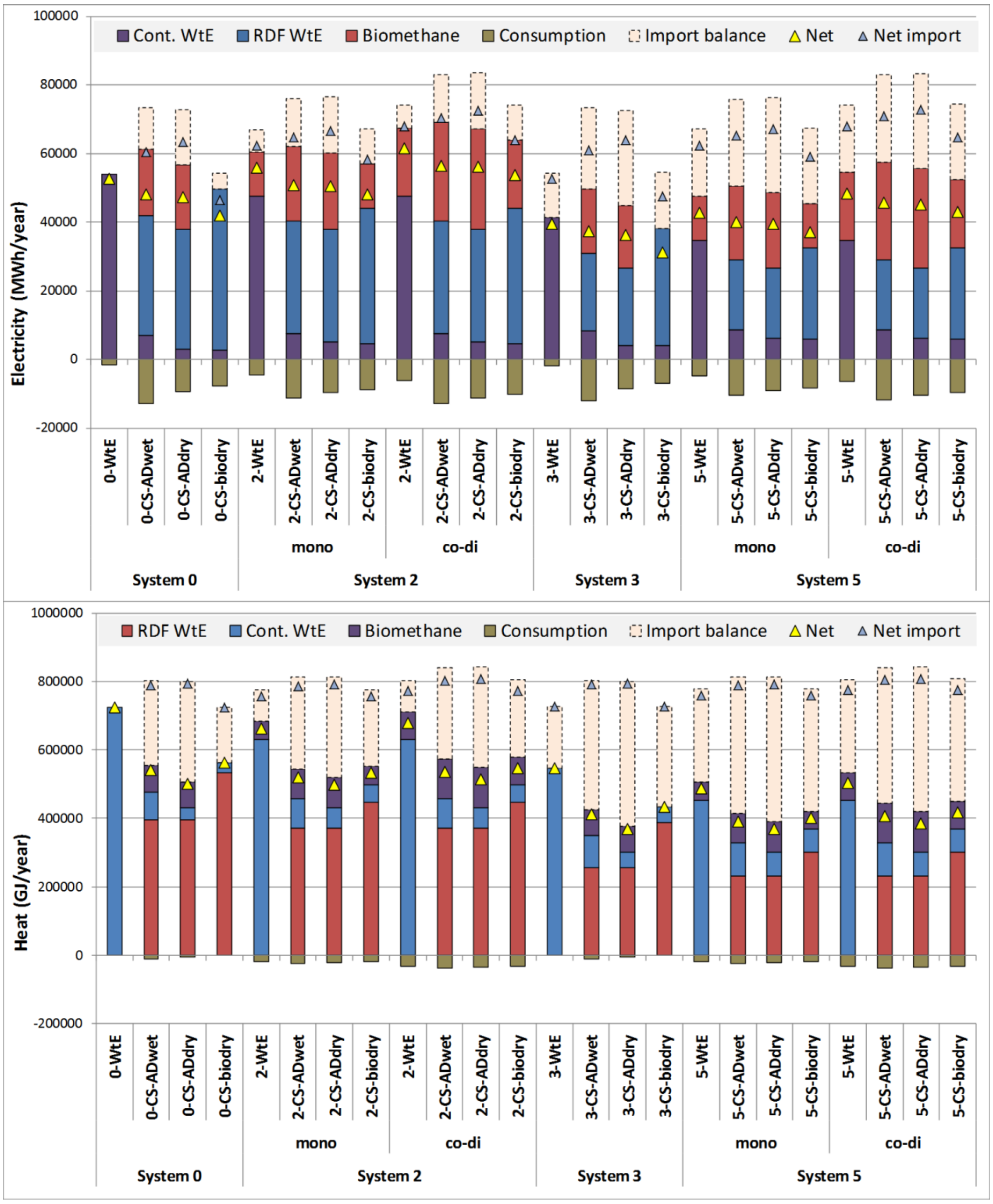


Figure 24: Electricity, heat production and import balance (positive values) and consumption (negative values), in 4 main systems, including 8 system variants with mono-digestion and manure co-digestion.

The introduction of the dual-stream collection of recyclable materials (3-WtE) has a significant effect in reducing the total electricity and heat that can be produced from remaining residual waste. The "trade-off" for achieving increased material recycling amounted to around 20% decrease in energy recovery compared to the reference system (0-WtE).

As can be observed in Figure 24, when cascading effects considering waste import are included in the model, more electricity and heat is in general produced in all system variants, compared to the reference system (0-WtE). This assumes the continued utilization of the incineration capacity in the region at the levels observed for 2013.

2.2.2 Carbon footprint results

Starting with the 24 main system variants, 16 of which can be modelled in 3 different perspectives (biowaste mono- and co-digestion), and adding the fact that all system variants can be modelled in 4 background time periods, this study has produced 224 (8*4+16*3*4) main sets of carbon footprint results. These 224 variants were further modelled considering 2 biomass marginal perspectives (progressive and dirty), each with 2 amortization periods. This brings the total number of unique variants and thus carbon footprint results to 896.

Additional results can be produced in a facile manner with the developed model by removing the cascading effects of combustible waste imports and by directing RDF to heat only boilers.

In order to present in a systematic way the wealth of information pertaining to the modelling results, we will structure this section on the basis of research questions which have fundamentally driven this work. The results presented in the main body of the report are based on the biomass marginal perspective of a progressive marginal (in the two amortization periods), while the results for the dirty biomass marginal perspective can be found in appendix 2.

2.2.2.1 Does it pay off to do central sorting of residual waste instead of direct incineration?

Figure 25 illustrates the carbon footprints of System 0 with incineration (0-WtE) and with central sorting (CS alternatives), for the 4 background time periods and considering biomass marginal amortization periods of 100 years (A) and 20 years (B).

As can be observed, all system variants were shown to save significant amounts of GHG emissions in all four background time periods. Savings related to material recycling remain constant in all three time periods, because the global energy marginal behind primary material production were considered unchanged in the time periods in question in this study. This is in contrast to savings related to energy production from waste in Denmark, which mostly decrease over time, in relation with the background energy marginals used in the model. The time periods take into consideration the major changes in the Danish energy system, which over time becomes less fossil dependent and therefore less carbon-intensive. The "quality" of electricity and heat production from waste, in terms of production flexibility, becomes important in the Mid-term and Long-term time perspectives, as for the Present time period flexible production was not credited differently than continuous production.

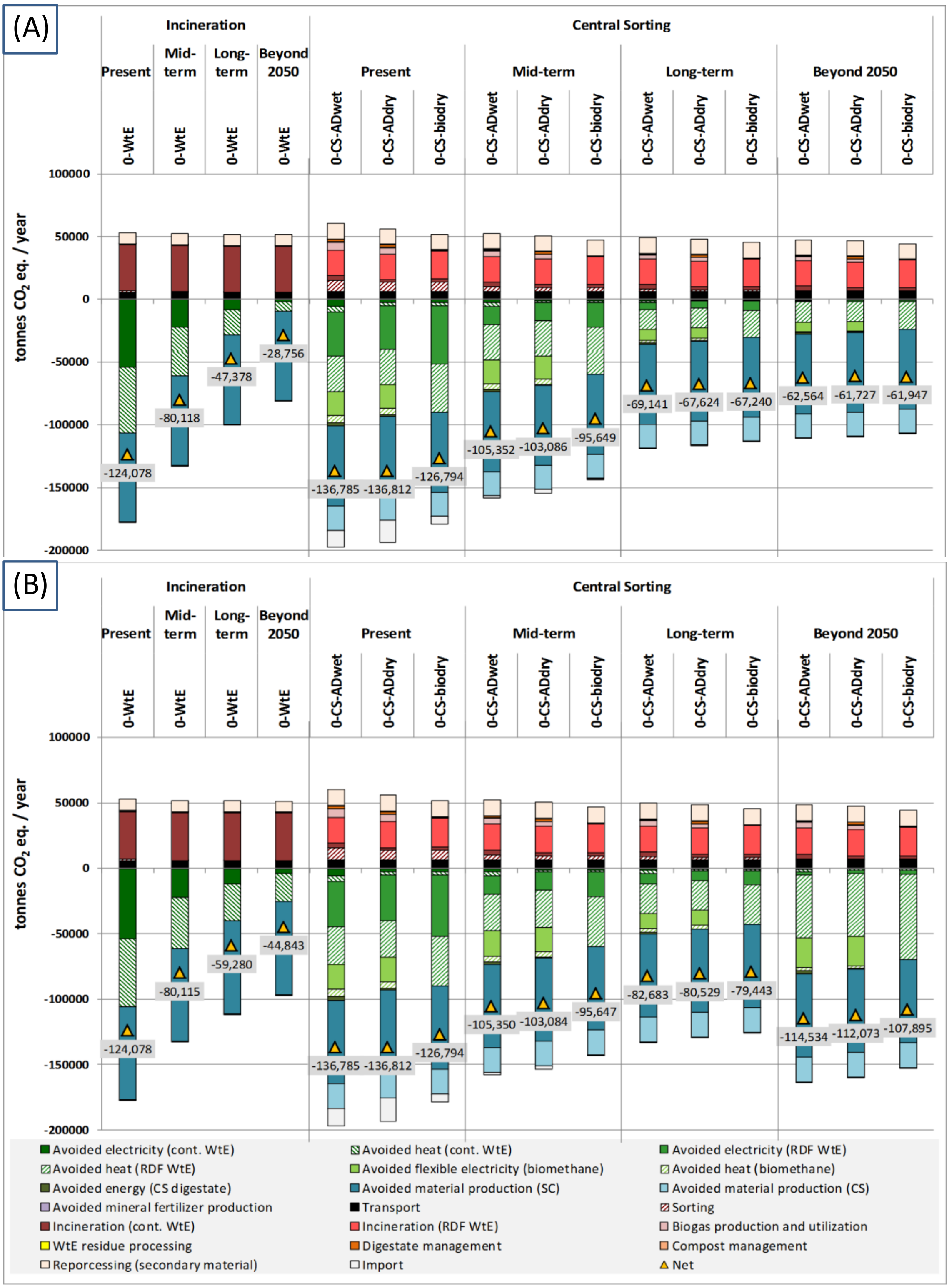


Figure 25: System 0 (existing separate collection) with WtE or CS of residual waste, with biomass marginal amortization of 100 years (A) and 20 years (B).

The different amortization periods, associated to emissions related to biomass provision, influenced the GHG savings related to energy in the Long-term and Beyond 2050 time periods. Specifically, it resulted in a similar increase in net savings for both 0-WtE and 0-CS in the Long-term, however net saving become nearly double for 0-CS in the Beyond 2050, compared to a 25% increase for 0-WtE.

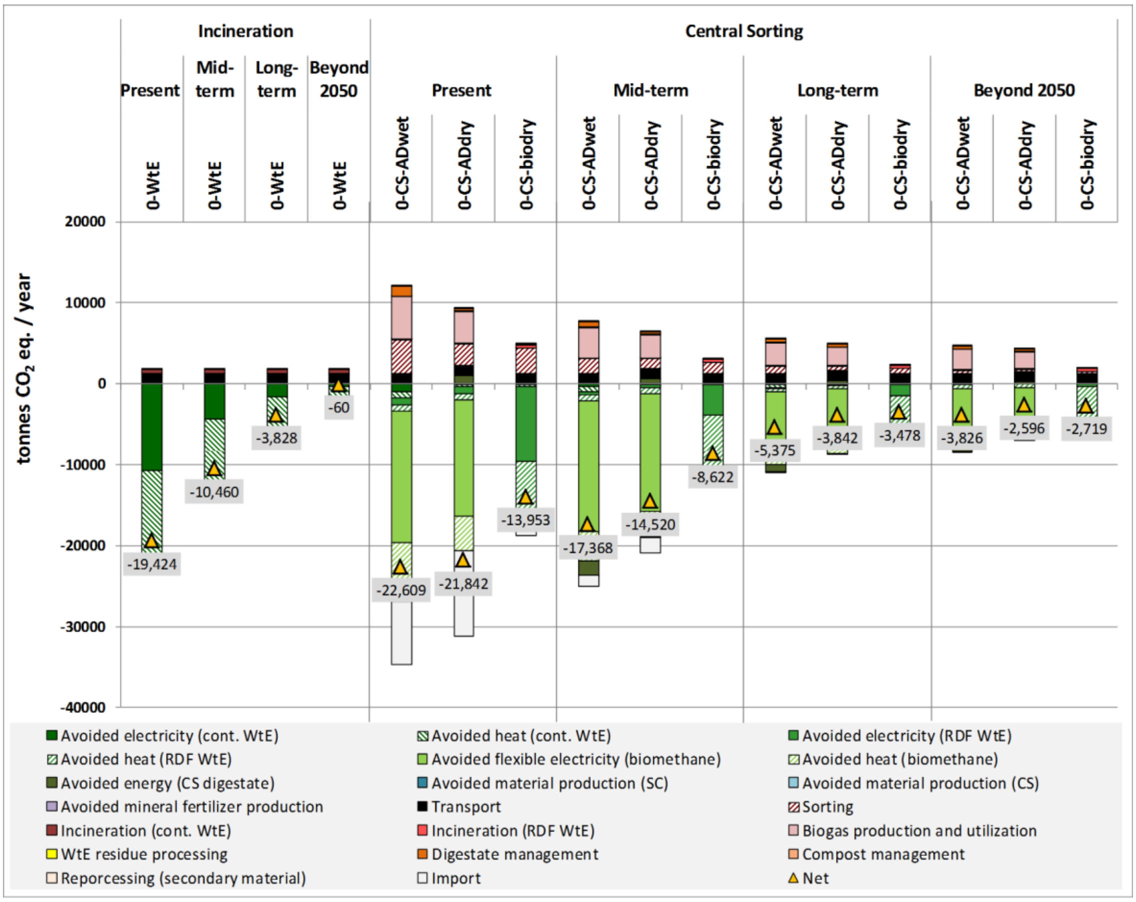


Figure 26: System 0 (existing separate collection) with WtE or CS of residual waste, results associated to the bio-fraction in the functional unit (100 years amortization for the biomass marginal).

A number of aspects can be delineated:

- In the Present time perspective, the reference system based on residual waste incineration and the new system design based on central sorting achieved similar net GHG savings (without the inclusion of waste import). 0-CS variants showed increased savings due to material recycling; however net system savings were reduced by a decrease in savings associated to energy production and due to additional system burdens (e.g. sorting, digestate management). Processing of residual waste in central sorting alongside existing incineration facilities in the region, lead to excess incineration capacity which could be filled with waste from outside Denmark. When the savings credited to combustible waste import are included, they benefit especially the two CS variants with biogas production, which then achieve higher GHG savings compared to 0-WtE (Figure 25).
- In the Mid-term perspective (compared to Present), net savings in the reference WtE-based system decreased by more than 30 %, compared to 15-20 % for the CS system variants. This difference translated into an advantage for CS variants which then were credited with 10-15 % more net GHG savings than the WtE variant. The difference was related entirely to production and flexible utilization of biomethane and RDF.

- In the Long-term perspective, savings in the reference system decreased by almost 50 % compared to the Present time perspective. In contrast the decrease is only 25-30 % for the CS system variants. The gap between CS variants and 0-WtE became more significant, at 20-25% difference in net GHG savings. This was again related entirely to production and flexible utilization of biomethane and RDF.
- Another interesting aspect can be pointed with regards to central sorting with biodrying (0-CS-Biodry), this variant achieved higher savings (compared to WtE) in the future background perspectives despite the fact that no biomethane is produced in this system variant, which highlights that the savings related to flexible heat production from storable RDF become important in the future.
- Looking at the bio-fraction in isolation, we can observe that CS variants with biogas perform similarly to WtE from Present to Long-term, however CS-Biodry performs worse than WtE. In the Beyond 2050, saving by WtE were near 0 while CS alternatives retained small GHG savings. The magnitude of the latter savings would double when considering a 20 year amortization period for the biomass marginal.

To conclude this section, the answer to the posed research question is, not surprisingly, dependent on the background conditions under which a system is assessed. Most important is the realization that under present conditions, central sorting of residual waste compared to efficient incineration does not entail a decrease in GHG emission savings, but could lead to an increase of savings due to freed incineration capacity. Moreover, if the modelled Mid-term, Long-term and Beyond 2050 background conditions are deemed realistic, then central sorting has a definitive advantage over direct waste incineration in the future.

2.2.2.2 Does it pay off to do separate collection of biowaste from households?

To answer this second research question, results from system variants without (0-WtE) and with biowaste separate collection (2-WtE) were compared (Figure 27A,B), taking into account the four background time perspectives. Biowaste from separate collection can be processed alone in a dedicated biogas facility, or it can constitute a co-substrate in manure-biogas facilities. Both options have been included in the present study. Furthermore, when biowaste is co-digested with manure, it will have two complementary/synergetic effects, whereby (1) it can create the opportunity for more manure to be directed towards biogas facilities, and (2) it will replace another, marginal, co-substrate, here modelled as maize for energy.

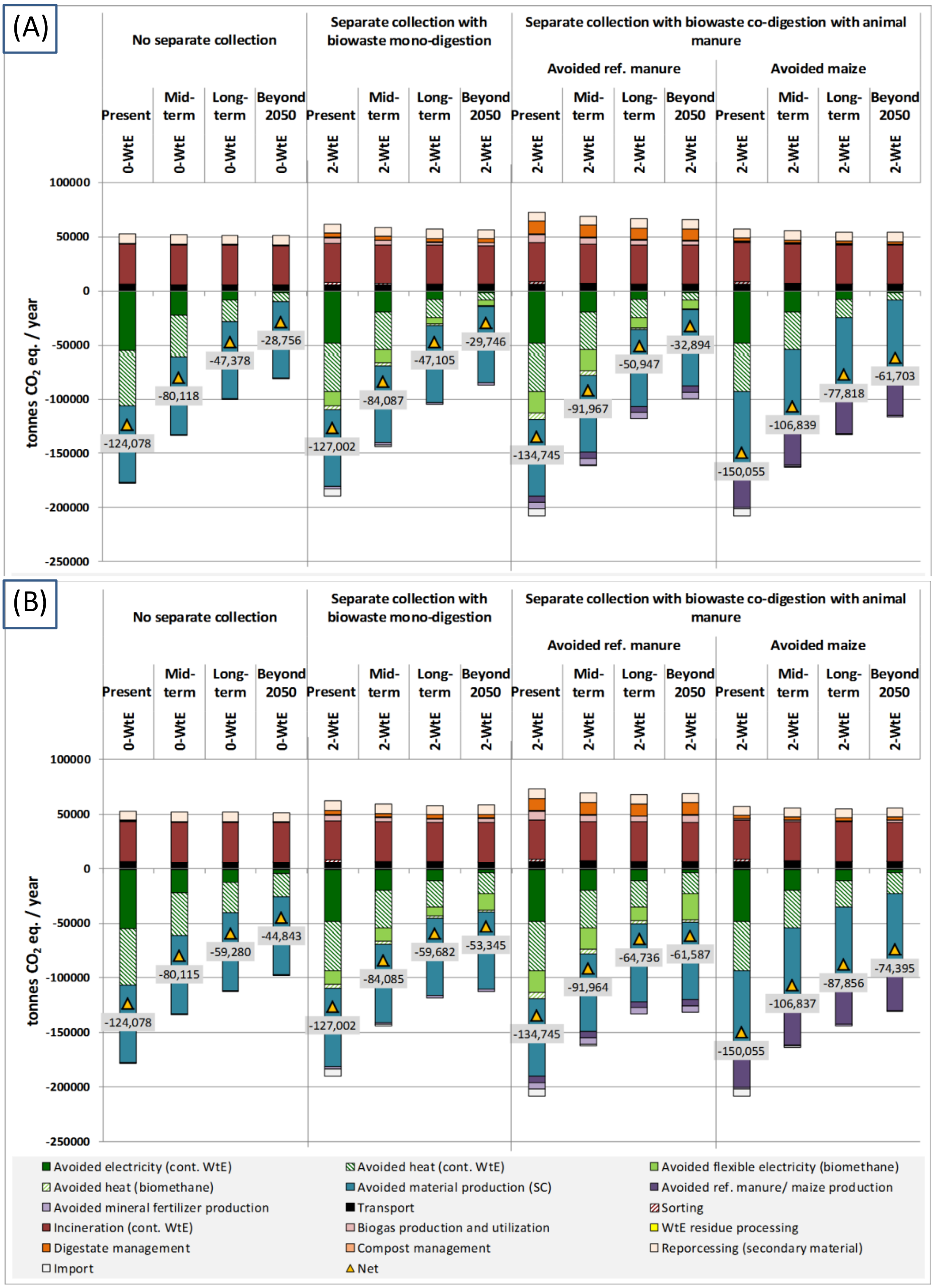


Figure 27: System 0-WtE (no separate collection of biowaste) and 2-WtE (biowaste collection in both single and multi-family residences), with biomass marginal amortization of 100 years (A) and 20 years (B).

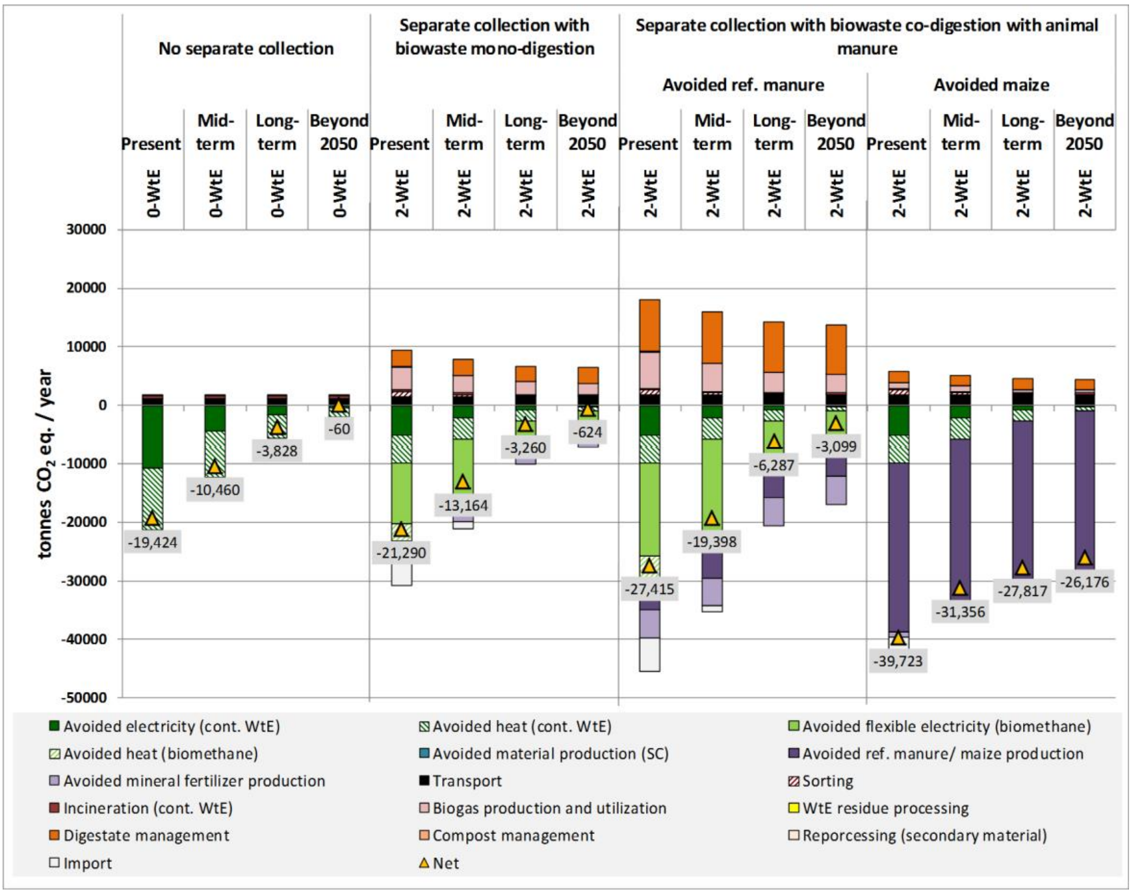


Figure 28: System 0-WtE (no separate collection of biowaste) and 2-WtE (biowaste collection in both single and multi-family residences), results associated to the bio-fraction in the functional unit (100 years amortization for the biomass marginal)

A number of aspects can be delineated from the comparative results:

- System variants with biowaste separate collection and processing in mono-digestion biogas facilities achieved roughly the same net GHG savings as the reference WtE-based system, in all four background time perspectives. Nevertheless, this result depends on foreground system choices, such as the efficiency of the WtE facilities (the three in the system), assumed biogas yield and fugitive CH4 emissions in the biogas production, upgrading and utilization chain.
- System variants with biowaste separate collection, followed by co-digestion with manure, achieved overall higher net GHG savings than the reference WtE-based system, in all four background time perspectives. (1) if biowaste co-digestion was credited with allowing for more manure-biogas to happen, and therefore avoiding the reference manure management (storage and direct spreading), system variants achieved around 5-10% more savings compared to the 0-WtE variant. (2) if biowaste was considered to avoid the production of an energy crop, in this study maize, the difference in savings increased to a considerable 20% to 100% between Present and Beyond 2050.

To conclude this section, biowaste separate collection was found advantageous in background conditions spanning 2012-2050+, considering especially the significant GHG reduction potential pertaining to co-digestion with animal manure. Considering the current and future political position in Denmark towards manure-biogas, it is expected that, in any case, if separate collection of biowaste does occur, biowaste would be used as a co-substrate due to the high demand of suitable biomass for co-digestion.

2.2.2.3 Does it pay off to do separate collection of biowaste and also recover organics for biogas in central sorting?

With separate collection of biowaste in both single and multi-family residences, applied in the whole region, we have estimated that between 50-60% of generated food waste could be captured and directed to biogas production. Therefore a significant share of the organic fraction would still be collected with residual waste. According to the output from the mass flow model, approx. 90% of the organics left in the residual waste, could be recovered in a concentrated stream in the central sorting facility. The effects of combining separate collection of biowaste and central sorting are illustrated in Figure 29A and B, taking system variant 2-CS-ADwet as an example.

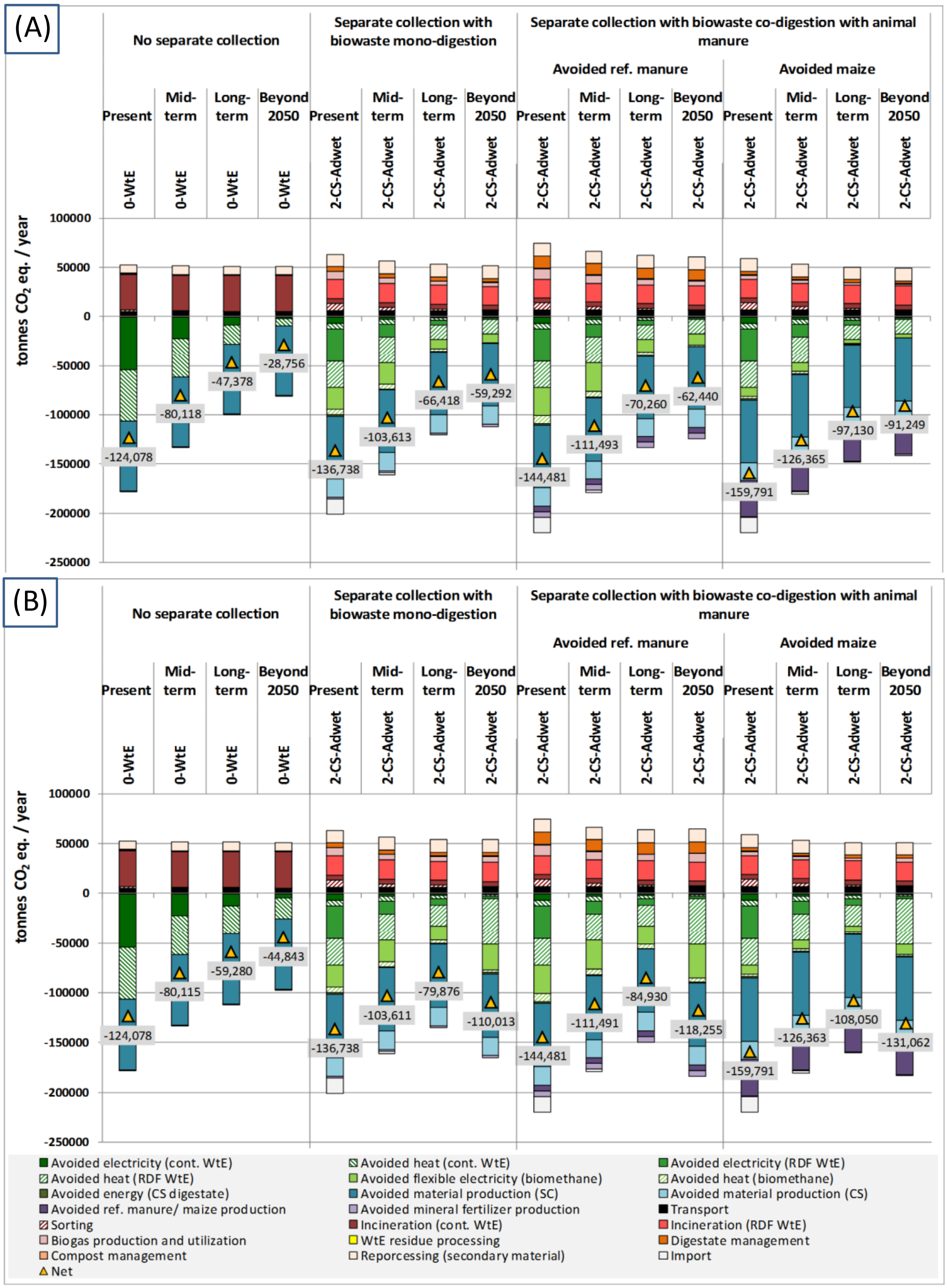


Figure 29: System 0-WtE (no separate collection of biowaste) and 2-CS-ADwet (biowaste collection in both single and multi-family residences, central sorting and wet digestion of bio-concentrate), with biomass marginal amortization of 100 years (A) and 20 years (B).

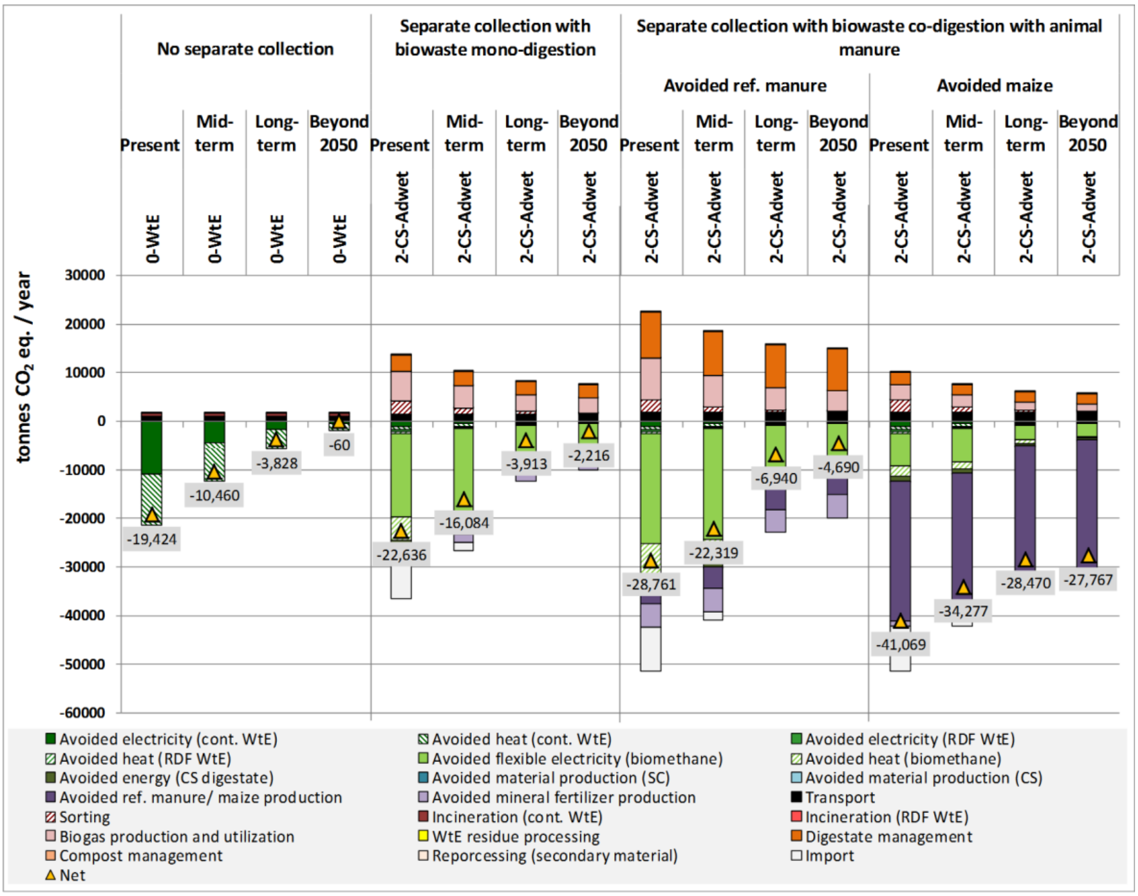


Figure 30: System 0-WtE (no separate collection of biowaste) and 2-CS-ADwet (biowaste collection in both single and multi-family residences, central sorting and wet digestion of bio-concentrate), results associated to the bio-fraction in the functional unit (100 years amortization for the biomass marginal)

A number of aspects can be delineated from the comparative results:

- With the addition of central sorting of residual waste, the system variant with separate collection of biowaste and mono-digestion thereof, achieved roughly the same GHG savings as the 0-WtE in the Present time perspective without the inclusion of waste import. With waste import included, as illustrated in Figure 29, the 0-CS variant achieved higher savings compared to 0-WtE. However, in the Mid-term, Long-term and Beyond 2050 time perspectives, the same variant gained a significant advantage over 0-WtE, which can be associated to extra biogas production after central sorting, followed by flexible electricity production (Figure 29).
- With the addition of central sorting of residual waste, the system variant with separate collection of biowaste and co-digestion thereof with animal manure, achieved substantially higher savings than the reference 0-WtE systems, in all three time perspective. These savings are also significantly bigger than in the systems with only separate collection of biowaste and residual waste incineration (previous research question), again reflecting the extra flexible electricity production due to sorting of organics in the central sorting facility.
- A significant share in the overall increase in savings observed in the Mid-term, Long-term and Beyond 2050 time periods for the CS variants is attributed to the use of storable RDF for heat production in the cold season.

- Compared to the results considering an amortization period for the biomass marginal of 100 years, the use of the 20 year amortization perspective, determined a stronger increase in potential savings especially in the Beyond 2050 time period.

To conclude, central sorting can make an important contribution to increasing flexible electricity production, even when biowaste is collected separately from households. This in turn was shown to have a positive impact, leading to even greater GHG saving a future dominated by renewable energy source, compared to employing separate collection alone.

2.2.2.4 *Does it pay off to change the various separate collection schemes for recyclable materials in Funen to a kerbside commingled scheme? And what could be the additional contribution to material recycling of central sorting?*

One of the main waste management system changes investigated in this study was regarding the implementation throughout the region of a homogenous kerbside collection scheme for dry recyclable materials. The mass flow model predicted that this approach would lead of a substantial increase in separate collection of recyclables from the current (reference) of 29% (relative to all daily generated domestic waste (FU)) to around 41%. Additionally, the model showed that a considerable amount of metals and plastics can be recovered directly from residual waste in the central sorting facility.

Figure 31 illustrates GHG burdens and savings associated with material recycling, broken down per material fraction, for System 0-WtE (existing separate collection), 0-CS (existing separate collection plus central sorting), 3-WtE (new kerbside dual-stream) and 3-CS (new kerbside dual-stream and central sorting).

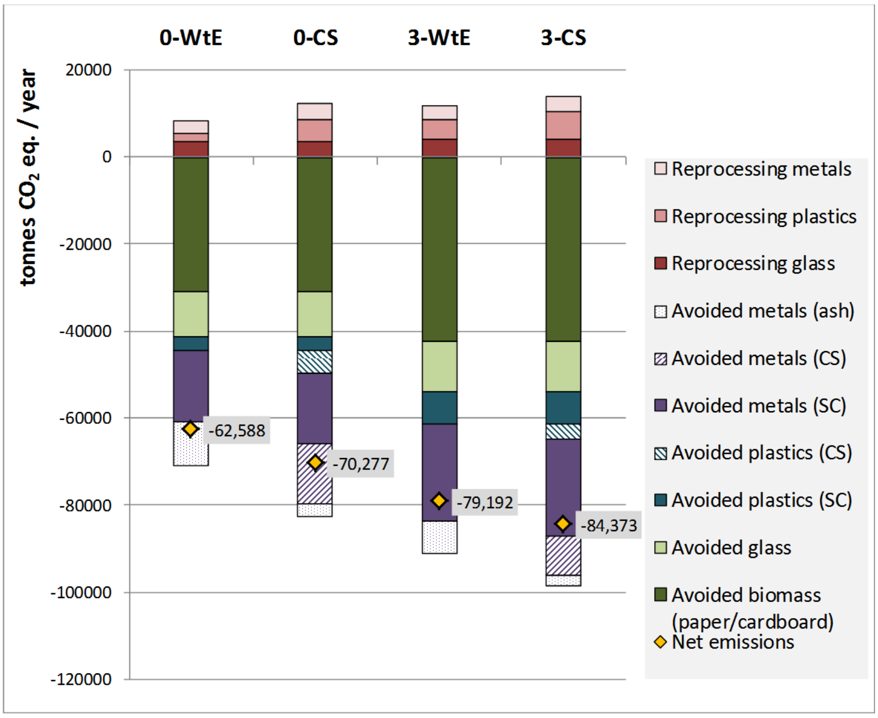


Figure 31: Burdens (positive) related to reprocessing to secondary materials, and benefits (negative) due to avoided primary material production.

A number of aspects can be delineated from the comparative results:

- The major share of savings in the reference system can be attributed to paper, cardboard and metals. Metals recovered from incineration ash contribute more than a third of the total GHG savings attributed to metals.
- Switching in System 0 from WtE to CS, could bring substantial GHG savings due to plastics and metals recovery (increasing savings from 62,000 to 70,000 tonnes CO_2 eq. /year).
- The transition from the existing disparate separate collection schemes in the region, to a kerbside dual-stream scheme (from 0-WtE to 3-WtE), could potentially increase savings by more than 30 % (from 62,000 to 79,000 tonnes CO_2 eq. /year).
- Even with efficient separate collection of recyclable from households, significant amounts of plastics and metals are still expected in residual waste. Having CS in the system could insure additional material recovery, and this is reflected in the additional GHG savings in system 3-CS.

From the perspective of material recovery for recycling, carbon footprint results suggest strong benefits by changing the existing collection schemes for dry recyclables, and by means of application of central sorting on remaining residual waste in the system.

2.2.2.5 What is the effect of combustible waste import in the Present and Mid-term time period?

There are four Danish incineration facilities included in the system model. Three are the main ones in use today in the region, additionally the incineration facility in Haderslev is modelled in Systems 3, 4 and 5 due to the fact that this facility is used to incinerate the sorting residues from the dual-stream.

In all systems, departing from the reference system (0-WtE), incineration capacity is made available (or overcapacity occurs) due to diversion of waste towards other types of treatment. This extra capacity can then be utilized to treat imported combustible waste, as explained in section 2.1.5.4, thereby not only maintaining the existing incineration facilities in the system, and the same energy output, but also helping reduce waste landfilling in countries which do not yet have enough treatment capacity.

Due to the nature of the changing energy system in Denmark, and according to the energy marginal used in this study to simulate these changes, waste import leads large GHG savings in the Present time period, to smaller GFG savings in the Mid-term and could even lead to net GHG burdens in the Long-term time perspective. In all cases the size of these benefits is different for the four facilities. The net benefits and a breakdown per contributing processes are illustrated in Figure 32 and Figure 33, considering the two types of avoided landfill modelled (low vs. high efficiency). To note, the net values used in the determination of the whole system carbon footprints has been the average of the two. As all processes are more or less equal in effect, except for energy recovery, the difference in savings is dependent on the energy recovery efficiency of each individual plant.

The figures show that the process of landfilling in the UK with high gas capture rates and gas utilization in a gas motor for electricity production, has net GHG savings (due to recovery of landfill gas and utilization thereof). Nevertheless, the net savings related to energy recovery in Denmark are on a much larger scale in the Present perspective, and therefore, this indicates a strong incentive to import waste today. In the Mid-term perspective, net savings become net burdens for all four plants.

In the case of landfills, that are less efficient in capturing gasses and the captured gas is only flared, strong savings by import arise for all four plants, even in the Mid-term perspective.

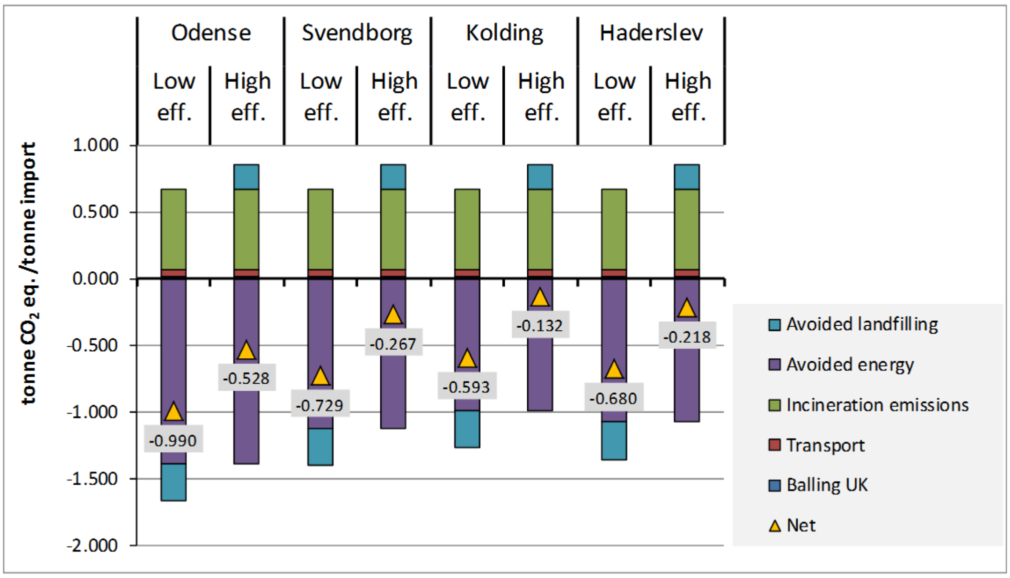


Figure 32: GHG balance for the import of one tonne of waste in the Present time perspective

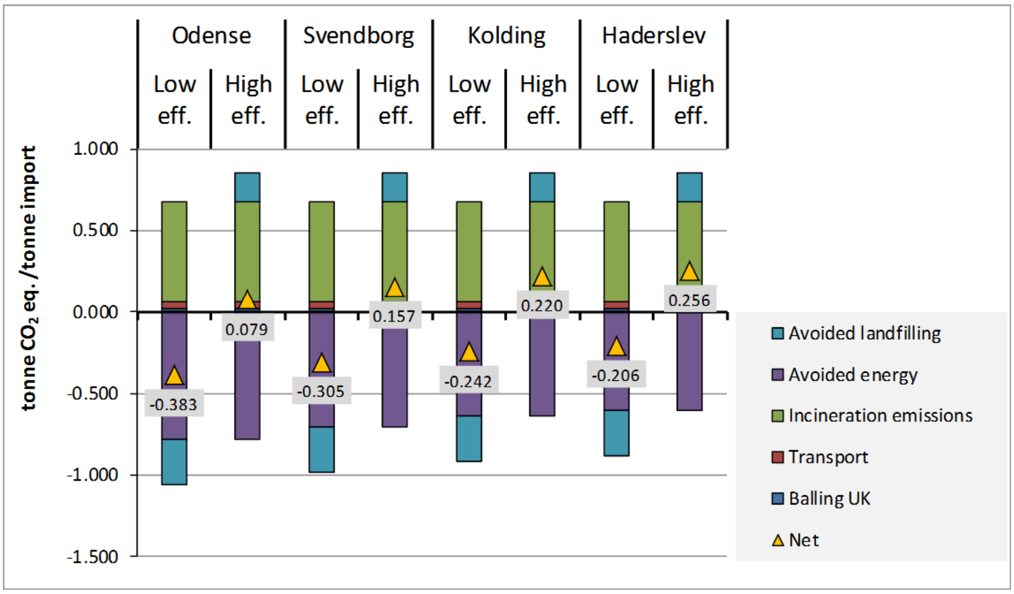


Figure 33: GHG balance for the import of one tonne of waste in the Mid-term time perspective

2.3 Conclusions to Part 2

2.3.1 Material and energy recovery

Following the Results and discussion section of Part 2, the main conclusions addressing mass flows, material and energy recovery are summarized in this section.

Materials recovery aspects:

- With consideration to the functional unit of this study, i.e. 157,000 tonnes of waste under the definition of daily generated domestic household waste, the current waste management system in the region of

Funen, achieved in 2013 a total separate collection efficiency of roughly 29% or around 45,000 tonnes. Metals recovery from incineration ash accounted for an additional 1-2 %, bringing the total recovery rate to 30-31 %.

- The five simulated alternative systems were shown to potentially increase separate collection to 50 % with source separation of biowaste (System 2), 41 % with separate collection of recyclables in kerbside dual-stream (System 3), and to 63 % with both biowaste and dual-stream separate collection (System 5).
- In system variants with WtE, 1-2 % additional material recovery was added by metal sorting from incineration ash, while in system variants with Central sorting, automatic sorting contributed an additional 5 % materials recovery in System 0-2 and 3 % in Systems 3-5, and therefore the actual total material recovery rate was 55 % in System 2, 44 % in System 3 and 66 % in System 5.
- Materials recovered for recycling contain impurities, fractions not suitable for recycling and many times moisture contents higher than virgin produced materials, thus the actual material recycling rates are always significantly lower than material recovery rates (Figure 22).

Energy recovery aspects:

- Net electricity recovery from waste (when system consumption was subtracted) was higher in every system simulated for the WtE variants compared to CS variants. Overall, there was a shift in the quality of recovered electricity from 100% continuous power production today to 25-50% flexible/regulating power production in system variants which include biogas production. The larger shares of flexible power production occur in variants with CS-ADwet/ADdry, both in systems with and without separate collection of biowaste.
- Net heat recovery was also shown to decrease significantly in CS system variants compared to WtE. However, between 50% and 80% of produced heat in CS variants is of a higher quality, given by the fact that it can be utilized entirely in the cold season (heat from storable RDF).
- When the continued use of the incineration capacity in the region is factored in the systems (in the Present and Mid-term), it is possible to see an overall increase of energy from waste in the region, despite the diversion of local waste from incineration facilities.

2.3.2 Carbon footprint of alternative systems

The global warming potential of total GHG emission effects of the 24 main system variants simulated in this study (6 main systems, each with 4 system variants) were assessed considering the development of the background energy system in Denmark towards 2050 in 4 different time perspective and whether biowaste was mono-digested or co-digested with manure. The most important concluding aspects are pointed below:

- The sole change from residual waste incineration to central sorting (both with the current separate collection system and the alternative dual-stream), was shown beneficial from a global warming perspective in all four background time periods. This was due to a threefold contribution by central sorting to: (1) GHG savings by material recovery for recycling, (2) GHG savings by contributing to flexible power and heat production, and (3) GHG savings from combustion of imported combustible waste, due to liberated incineration capacity.
- Biowaste separate collection was found to contribute to significant GHG savings compared to incineration of the organic fraction if co-digested with manure. With regard to the two consequential perspectives, i.e. avoided reference manure management and avoided production of energy crops, the

latter was found to have the largest GHG savings potential, due to avoided direct and indirect land use changes associated with the production of energy crops.

- System variants with separate collection of biowaste (co-digestion) and central sorting of residual waste achieved higher GHG savings than variants with biowaste and waste incineration. In fact, the former variants achieved the biggest potential savings of all variants in all three time perspectives, due to the cumulative effect of favouring factors described in the two previous points.
- Changing the different existing separate collection systems for recyclable materials to a homogenous kerbside system (the dual-stream) was shown to be beneficial from global warming perspective, due to large potential GHG savings credited through avoided material production from virgin sources. In addition, despite the fact that central sorting only contributed with around 3-5 % to overall material recovery in the systems, GHG savings associated with recycling of materials from CS contributed with 7-10 % of total system savings.

Overall, the system differences or changes from the current waste management in the region, which were modelled in this study, became more important moving towards the Long-term and Beyond 2050 simulated background conditions. This assessment strongly indicates that from a global warming perspective there are considerable advantages associated with an evolution of waste management in the region towards greater synergy with the background systems of the future and also towards increased recycling.

3 Part 3: Economic assessment

Part 3 of this report documents the methods and results obtained following the budget-based economic analysis of selected full system presented in Part 2 of this study.

3.1 Methods

3.1.1 Budget economic analysis

The method used to compare the existing and possible alternative waste management systems in the region of Funen was a budget-based economic analysis, which constitutes a total balance of costs and benefits over the whole system, without the inclusion of current taxes and subsidies. Moreover, the difference between a budget economic analysis and a socio-economic analysis is that the budget economic analysis includes only the direct financial cost / benefits and no externalities (costs associated with environmental burdens or savings). Tax distortion losses were not included. Agricultural and environmental beneficial effects of biogas production are not valued in this report, and are not recognized.

The cost elements included in this analysis are: (1) investment costs, (2) annualized capital expenditure (Capex), (3) operational expenditure (Opex) and (4) revenues from sale of functional outputs, such as materials and energy. The results are expressed as total net yearly system costs.

The economic analysis covers the first three time periods included in the study, with some important limitations. Background energy and energy feedstock prices have been projected for the future time periods based on available projections from the Danish Energy Agency and Energinet. However, no projections have been made for materials sales prices, and also for potential capital and operational expenditure changes.

3.1.1.1 Investment and capital expenditure

Investment costs were compiled from a variety of sources, such as data provided by the municipalities in the region for existing facilities and collection systems, Danish benchmarking reports in the waste sector (RenoSam, 2011), the Danish Energy Agency and Eneginet.dk technology catalogue (DEA and Energinet, 2012) and a number of consultancy reports and research literature (Ea Energianalyse, 2014, Møller et al., 2013, Cimpan et al., 2015a). Investment costs for central sorting and biowaste pre-treatment have been determined in this work directly through techno-economic modelling.

Capital expenditure (Capex) represents costs related to investment and borrowing of capital. Since all investments have a lifetime below 35 years, a fixed interest rate of 4 % was used according to the recommendation of the Danish Ministry of Finance (Danish Ministry of Finance, 2013). The two main equations used to calculate Capex are presented below:

$$Capex=IC*CRF \quad (1)$$

$$CRF=i*(1+i)n/[(1+i)n-1] \quad (2)$$

IC denotes *total investment cost*.
CRF denotes *capital recovery factors* which are calculated by using i, which is the interest rate of borrowing capital and n, the life time of assets. The life time of assets (or depreciation periods) is different for buildings (20-25 years), fixed processing equipment (8-15 years) and mobile equipment (5-8 years).

3.1.1.2 Operational expenditure

Operational expenditure (Opex) comprises cost of labour, utilities (electricity, heat and fuel), repair/maintenance costs and insurance. Most data on operational and maintenance costs have been compiled from the same sources as investment costs.

3.1.1.3 Revenues from sale of functional outputs

The prices or value of recyclable materials from separate collection and following central sorting of residual waste, used in the model, represent the average of a quite broad interval of variation. Both the minimum and maximum limits of these intervals can be changed in order to test different price ranges. Sources for price data have constituted the municipalities in the region (especially prices for materials collected at recycling centres) and consultancy reports such as Møller et al. (2013) and Jakobsen et al. (2014). Prices for materials recovered in central sorting were estimated based on pure material content and price levels from similar facilities placed in Germany.

3.1.2 Selected systems and costing alternatives

Table 21 below gives an overview of the systems include in the economic analysis.

Table 21: Overview of systems included in the economic analysis

Systems archetypes	Separate collection	Treatment of remaining residual waste			
		WtE: Incineration CHP	*CS-ADwet: Central sorting with wet digestion*	*CS-ADdry: Central sorting with dry digestion*	*CS-Biodry: Central sorting with biodrying*
System 0	Existing schemes	0-WtE	0-CS-ADwet	0-CS-ADdry	0-CS-Biodry
System 2	Existing schemes + Biowaste SF and MF	2-WtE	2-CS-ADwet	2-CS-ADdry	2-CS-Biodry
System 3	Dual-stream	3-WtE	3-CS-ADwet	3-CS-ADdry	3-CS-Biodry
System 5	Dual-stream + Biowaste SF and MF	5-WtE	5-CS-ADwet	5-CS-ADdry	5-CS-Biodry

Four different options on the use of biomethane and RDF were considered in the cost calculations, in order to explore if overall system economic efficiency can be enhanced. The options were:

- Biomethane electricity and heat production and RDF CHP
- Biomethane sale and RDF CHP
- Biomethane electricity and heat production and RDF heat only boiler
- Biomethane sale and RDF heat only boiler

3.1.3 Inventory

3.1.3.1 Collection

Sizing of the collection system

The collection schemes are different for single-family and multi-family residences. Smaller individual bins are allocated to single-family households (0.14-0.24 m^3), while larger common bins are shared by more families in the case of multi-family residences (0.40 and 0.66 m^3). The types of bins allocated are presented in Table 22.

Table 22: Types of collection containers in the systems

	Single-family kerbside					Multi-family kerbside				Cube system	
System	Residual	Paper	Other	Dual-stream	Biowaste	Residual	Paper	Dual-stream	Biowaste	Paper/ Card	Glass
0-WtE	190 L	140 L	240 L		140 L	400 L/660 L	660 L			2500 L	2500 L
0-CS	190 L	140 L	240 L		140 L	400 L/660 L	660 L			2500 L	2500 L
2-WtE	140 L	140 L	240 L		140 L	400 L/660 L	660 L		400 L	2500 L	2500 L
2-CS	140 L	140 L	240 L		140 L	400 L/660 L	660 L		400 L	2500 L	2500 L
3-WtE	190 L			240 L	140 L	400 L/660 L		400 L/660 L			
3-CS	190 L			240 L	140 L	400 L/660 L		400 L/660 L			
5-WtE	140 L			240 L	140 L	400 L/660 L		400 L/660 L	400 L		
5-CS	140 L			240 L	140 L	400 L/660 L		400 L/660 L	400 L		

In the case of single-family residences one bin for each collected stream is allocated to each individual residence, while for multi-family residences the number of families connected to the larger bins was calculated. In the latter case, it was assumed that on average there is a 50:50 distribution, in the region, of residences that use 0.40 m^3 and 0.66 m^3 bins. The number of families connected to one bin was then calculated based on the size of bins, number of emptying/collections per year and the volume of the collected waste stream. For both types of residences, the frequency of collection was calculated based on the amount of waste generated per year, accounted in volume, with the assumption that bins are filled 70-80 % upon collection. Collection frequencies and number of families connected to one bin are presented in Table 23 and Table 24.

In the existing collections schemes in the region, cube collection of paper and glass is implemented in several municipalities. It was assumed that on average 200 residences are connected to one cube, which is collected every month. The number of cubes needed was then calculated based on the total quantity of paper and glass collected in the cube system in 2013.

Table 23: Collection frequencies (no. /year)

	Single-family kerbside					Multi-family kerbside				Cube system	
System	Residual	Paper	Other	Dual-stream	Biowaste	Residual	Paper	Dual-stream	Biowaste	Paper/ Card	Glass
0-WtE	26	13	13		26	26	13			13	13
0-CS	26	13	13		26	26	13			13	13
2-WtE	26	13	13		26	26	13		52	13	13
2-CS	26	13	13		26	26	13		52	13	13
3-WtE	26			13	26	26		13			
3-CS	26			13	26	26		13			
5-WtE	26			13	26	26		13	52		
5-CS	26			13	26	26		13	52		

Table 24: Number of families connected to collection containers

	Single-family kerbside					Multi-family kerbside				Cube system	
System	Residual	Paper	Other	Dual-stream	Biowaste	Residual	Paper	Dual-stream	Biowaste	Paper/ Card	Glass
0-WtE	1	1	3		1	7	15			200	200
0-CS	1	1	3		1	7	15			200	200
2-WtE	1	1	3		1	9	15		30	200	200
2-CS	1	1	3		1	9	15		30	200	200
3-WtE	1			1	1	8		8			
3-CS	1			1	1	8		8			
5-WtE	1			1	1	10		8	30		
5-CS	1			1	1	10		8	30		

Collection costs

Collection costs in this analysis included investment and maintenance of collection containers (different size bins and cubes) and container emptying prices. The latter accounts for investment and operational costs (i.e. fuel, salaries, maintenance) related to collection trucks. Base data was taken from Møller et al. (2013) and corroborated with data provided by municipalities in the region (e.g. Odense, Kerteminde, Assens, Faaborg-Midtfyn and Svenborg).

Additional costs, which have not been included in this study, are related to plastic or paper bags used in collection and costs related to information campaigns in the introduction of new collection schemes.

Table 25: Main costing parameters for waste collection

	Volume	**Price**	**Lifetime**	**Capital expense**	**Maintenance**	**Emptying price**
	m^3	kr./container	years	kr./year	kr./container/year	kr./emptying
Kerbside bin	0.14	190	8	28	8	12
Kerbside bin	0.19	220	8	33	9	13
Kerbside bin	0.24	240	8	36	10	14
Kerbside 2-compartment bin	0.24	350	8	52	14	15
Kerbside bin	0.40	800	8	119	32	22
Kerbside bin	0.66	900	8	134	36	23
Cubes paper	2.50	5500	10	678	220	100
Cubes glass	2.50	6000	10	740	240	100

3.1.3.2 Long distance transport costs

Unit costs (kr./tonne*km) were based on the work of COWI (Møller et al., 2013) and they account for differences in truck load and truck type used in the transportation. If transport to the first process in the system was less than 15 km, it was included in the price of emptying bins.

Table 26: Distance and cost of long-distance transport

	Cost	Transfer share and distances		Final treatment distances		Transfer costs	Final treatment costs	
		Share	Distance	System 0-2	System 3-5		System 0-2	System 3-5
	Kr./tonne*km	%collected	km	km	km	kr./tonne	Kr./tonne	Kr./tonne
Paper	0.28	50 %	50	300	200	14	84	56
Cardboard	0.32	50 %	50	300	200	16	96	64
Foil plastics	0.35	-	-	570	460	-	200	161
Hard plastic (polymer)	0.35	-	-	-	460	-	-	161
Hard plastic mix	0.35	-	-	570	-	-	200	-
Fe-metals	0.02	-	-	7500	7500	-	150	150
NF-metals (Al, heavy NF)	0.28	-	-	700	700	-	196	196
Glass	0.28	-	-	100	200	-	28	56
Metal mix	0.28	50 %	50	-	-	14	-	-
Digestate	0.43			10	10	-	4.3	4.3
Biowaste	0.28	100 %	100	-	-	28	-	-
Residual waste	0.28	50 %	50	-	-	14	-	-
Dual-stream	0.32	100 %	150	-	-	48	-	-

3.1.3.3 Costs associated with sorting and waste treatment

The cost of treatment for the different plants and their capcities are presented in Table 27.

Table 27: Investment and processing costs for the different waste treatment plants

		Capacity	Investment	CAPEX	OPEX	Total cost	Total cost
Facility	unit	unit/year	million kr.	million kr./year	million kr./year	million kr./year	kr. /unit
Recycling centre	tonnes w.w.	n.a	n.a	n.a	n.a		400
Paper sorting and balling	tonnes w.w.	50,000	30.00	2.50	3.50	6.00	120
Metal sorting	tonnes w.w.	n.a	n.a	n.a	n.a		50
Dual-stream 1	tonnes w.w.	100,000	40.00	3.33	4.67	8.00	80
Dual-stream 2	tonnes w.w.	50,000	89.28	11.16	22.32	33.48	670
Organics pulper	tonnes w.w.	60,000	36.90	4.30	4.14	8.44	141
CS-ADwet	tonnes w.w.	100,000	126.57	16.97	23.90	40.87	409
CS-ADdry	tonnes w.w.	100,000	208.74	22.97	25.81	48.78	488
CS-Biodry	tonnes w.w.	100,000	159.42	18.98	24.23	43.21	432
Incineration	tonnes w.w.	200,000	1000.00	73.58	69.00	142.58	792
Biogas plant (CS-ADwet)	tonnes w.w.	300,000	82.50	6.07	7.60	13.67	46
Biogas plant (separate collection)	tonnes w.w.	300,000	82.50	6.07	7.60	13.67	46
Biogas upgrading	Nm^3	8,000,000	20.69	2.55	1.55	4.10	0.51
Gas motor	MWh el.	49,800	77.30	5.69	3.41	9.10	183
Digestate dewatering	tonnes TS	n.a	n.a	n.a	n.a		2000
Sludge incineration	tonnes w.w.	n.a	n.a	n.a	n.a		450
Composting facility	tonnes w.w.	n.a	n.a	n.a	n.a		200
District heating boiler (RDF)	GJ	1,440,000	409.20	30.11	35.79	65.90	46

Material quality control and sorting plants

The cost of using the recycling centres was estimated to an average 400 kr. per tonne waste. This cost covers capital and operational expenditure only, and does not cover disposal costs (since recyclable materials are not disposed of) or revenues from material sales. The main information sources were the benchmarking report by RenoSam (RenoSam, 2011) and information delivered by the municipalities.

The cost of quality check and bailing of paper (by operators such as Marius Pedersen A/S) and the cost of sorting the dual-stream mixture of paper, cardboard and plastic foil, were based on different size paper sorting plants presented in Møller at al. (2013) and Jakobsen et al. (2014).

The cost to sort the dual-stream mixture of metals, glass and plastics was estimated based on costs associated with a medium size packaging sorting plant in Germany (Cimpan et al., 2015b).

Waste incineration

A number of different sources were used to estimate investment and operational costs for incineration.

First, it has to be stated that the actual costs of incinerating waste in the three existing plants in the region has not been used in this economic assessment. The costs used reflect (similar to the central sorting plant) the establishment and running of a new plant with a capacity of 200,000 tonnes/year. The main information sources were the Energistyrelsen's technology catalogue (DEA and Energinet, 2012), the benchmarking report by RenoSam (RenoSam, 2011) and project data collected at SDU from facilities such as Reno-Nord (Aalborg).

Secondly, it was assumed that when less residual waste is available in the system, the cost to process remaining waste will not be affected. This is based on the condition that incineration capacity will always be used, in this case for example with waste imported from outside Denmark.

Biowaste pre-treatment and digestion

Economic data on biowaste pre-treatment by pulping (Ecogi/Cellwood) could be found in the report by Niras (2013).

As a baseline it was assumed for all systems with biogas production that the capacity of the biogas plants was not constrained by the amount of organics used in the system for biogas production. This means that we have not considered the establishment of relatively small dedicated plants for the organics separated in the systems. Quite the contrary, it was assumed that biowaste is transported around 100 km to a large (300,000 tonnes/year) facility placed in Jutland, where both the pre-treatment and digestion takes place. Similarly, it was assumed that organics separated in the central sorting process for wet digestion (CS-ADwet), are added to a larger facility (300,000 tonnes/year) which could also be treating sewage sludge.

Investment and operational costs for biogas plants were based on the report made for the Energistyrelsen's Biogas Taskforce by Ea Energianalyse (Ea Energianalyse, 2014).

Biogas upgrading and utilization

The biogas produced in the systems was upgraded to natural gas quality, pressurized and fed into the gas grid. The upgrade can be done at the biogas plants or in one or more major upgrade facilities. Besides actual upgrading, the process includes pressurizing the biomethane to pressure in the natural gas network

(40 bars at major up-grading facilities), equipment for measuring gas quality, odorisation and the connection to the grid. The costs to the service line were not included as they are heavily dependent on the actual distance from the biogas plant to natural gas network.

The capacity of upgrading facilities is typically given in Nm^3 biogas on the input side. The capacity is here counted on an operating capacity in Nm^3 CH_4 on the input side assuming an oversizing of just over 10% of the throughput production, taking into account that biogas production will never be completely constant. The 10% oversizing corresponds to approximately 8000 full load hours at full planned load. In this work it was considered that the upgrading facility is rather large, having the capacity of 1000 Nm^3 biogas/h. A total investment, including upgrading, methane oxidation and gas network injection (compression of 7 bar (outlet pressure from the water scrubber system) to 40 bar (network pressure)) of 35,000 kr./Nm^3 CH_4/h was used according to Ea Energianalyse (2014).

Biomethane is assumed used for production of flexible electricity (and heat) by combustion in gas motors. Investment and operational costs were based on Energistyrelsen's Technology catalogue.

Central sorting

CS-ADwet investment and operational cost data presented in Table 27, accounts for mechanical processing and refining of separated organics in a pulper. In this central sorting variant, digestion is not directly included in the costs of the central sorting plant. CS-ADdry accounts for mechanical processing and dry digestion, while CS-Biodry accounts for mechanical processing and biological drying units.

The investment and operational costs are based on a techno-economic model established at SDU, which is unpublished at the moment this work takes place.

3.1.3.4 Material sales price data

The price interval of variation considered in this study and the average prices used to estimate revenues from material sales are presented in Table 28.

Table 28: Material prices

	Materials from separate collection			Materials from central sorting		
	Low limit (kr./tonne)	High limit (kr./tonne)	Average used (kr./tonne)	Low limit (kr./tonne)	High limit (kr./tonne)	Average used (kr./tonne)
Paper	500	1000	750			
Cardboard	400	800	600			
Foil plastics	400	2000	1200	300	1500	900
Hard plastic (polymer)	1000	2500	1750	700	2000	1350
Hard plastic mix	-2000	0	-1000			
Fe-metals	1000	1500	1250	400	800	600
NF-metals (Al, heavy NF)	4000	8000	6000	2000	4000	3000
Glass	-100	-50	-75			

3.1.3.5 *Energy and energy feedstock price data*

All future energy or fuel prices were calculated as socio-economic prices and therefore do not include taxes and subsidies. It should be emphasized that the price estimates are subject to great uncertainty, however the methods and sources behind the estimations are presented transparently unde r this section.

Table 29: Energy and energy feedstock prices in the three time perspectives

		Present 2012-2020	Mid-term 2020-2035	Long-term 2035-2050	
Energy prices	unit	kr./unit	kr./unit	kr./unit	Source
Electricity continuous	MWh	290	430	500	Energinet.dk
Electricity flexible	MWh	290	500	590	Energinet.dk
Heat continuous	GJ	73	67	74	Own calculation based on marginal
Heat flexible	GJ	73	80	88	Own calculation based on marginal
Feedstock prices	unit	kr./unit	kr./unit	kr./unit	Source
Natural gas	GJ	70	77	82	DEA (2014)
Natural gas	Nm^3	2.8	3.1	3.3	Based on LHV of natural gas
Biomethane	Nm^3	2.8	3.1		Assuming the same value as natural gas
SNG from biomass	GJ			200	Tunå and Hulteberg (2014) and unpublished data from Ea Energianalyse
Biomethane	Nm^3			6.4	Calculated based on 2/3 SNG and 1/3 natural gas
Straw	GJ	41	52	56	DEA (2014) and Bang et al. (2013)
Wood chips	GJ	50	60	65	DEA (2014) and Bang et al. (2013)

Future electricity and heat production prices

The current electricity price is taken as an average from Nord Pool Spot market for 2013. Price levels for 2035 were estimated based on simulated time series by Energinet.dk. The simulations were based on a scenario where the Danish environmental policy is slightly more ambitious than the current European agenda and that Denmark maintains the level of collaboration with other European countries that exists today.

Just like with the marginal electricity production used in the carbon footprint assessment, in the Present time perspective no difference (price) was assumed between flexible and continuous electricity production. Due to high penetration of wind and solar electricity by 2035, it was estimated that around 50 % of the time in a year, all electricity demand would be met by wind and solar production (surplus conditions), and the remaining 50 % it would be necessary to employ other production means (deficit conditions). Naturally, there are substantial price differences between periods with deficit and surplus electricity. Based on the price projection from Energinet.dk, we have taken the 2035 year average as the price/value for continuous electricity production from waste, and the average of the deficit periods as the price/value for flexible electricity production. No price projections exist for 2050, motivated by large uncertainty. In order to account for possible price increases between 2035 and 2050, we have made the rough assumption that the 2035 average of the deficit periods could represent the price for contin uous electricity in 2050, while for flexible electricity we have taken an average price representing the 5 % of the same year with the highest market prices.

Heat production in the waste management system replaces district heating produced from other sources. District heating production prices in the three time perspectives were based on the marginal heat assumed for the period (either continuous or flexible), and are determined by summing up production costs and feedstock prices (as delivered to the heat plant). Production costs for district heating based on natural gas, biomass and based on electric heat pumps are presented in Table 30, while feedstock price projections are presented in Table 29.

Table 30: Production costs for district heating

		Capacity	Investment	CAPEX	OPEX	Total cost	Total cost
Facility	unit	unit/year	million kr.	million kr./year	million kr./year	million kr./year	kr. /unit
District heating boiler, wood-chips	GJ	345,600	71.42	5.26	3.86	9.11	26
District heating boiler, gas	GJ	288,000	7.44	0.55	0.28	0.82	3
District heating, heat pump	GJ	288,000	50.59	3.72	0.41	4.13	14

Future natural gas prices

The current gas price is based on the market price on Gaspoint Nordic prices. The future natural gas price is based on the New Policy Scenario in the report World Energy Outlook 2013 published by the International Energy Agency. The prices projected from 2015 to 2035 and converted in Danish kroner (kr./GJ) were published by the Danish Energy Agency (DEA, 2014). The prices include transport and other fees as delivered at a Danish power plant. The average yearly price increase between 2015 and 2035 was assumed to continue towards 2050.

In the costing alternative where biomethane is directly sold on the market, and therefore the energy production itself is not accounted, it was assumed that the maximum value that the biomethane can earn is the price of natural gas.

Future biomass prices (wood chips and straw)

Current prices for wood chips (and straw) and projections between 2012 and 2050 were based on DEA (2014) and Bang et al. (2013). The prices include all fees including transport to the gate of a Danish power plant. The basis of the projection is an assumption of a regional and global demand for biomass for energy as described in the New Policy scenario in the IEA publication World Energy Outlook 2012.

Future SNG from biomass

According to the assumptions taken in this study, In the Long-term (2035-2050) time perspective, 75% of the flexible electricity marginal is gas-based. Specifically, that is made up of 1/3 natural gas and 2/3 biomass-based synthetic gas. In the costing alternative where biomethane is directly sold, it has then been assumed that biomethane would have the same value as the gas mixture in the flexible electricity marginal.

The price for biomass-based SNG was estimated by summing together the cost for SNG production in Tunå and Hulteberg (2014) and the additional cost to upgrade CO_2 by hydrogenation, according to calculation made by Ea Energianalyse (unpublished).

3.2 Results and discussion

3.2.1 Overall results

An overview of net yearly system costs is illustrated in Figure 34, in all three time periods. The net system cost was calculated by summing all system costs, followed by subtraction of all system revenues (from sale of functional outputs). A breakdown showing the contribution of different parts of a system is illustrated in Figure 35, for the first costing alternative, i.e. with biomethane utilization, while figures for the three other costing alternatives are placed in the appendix 3 of this report.

In Figure 34, we can observe that net system costs for all systems were highest in the Present time perspective, and then decreased in the Mid-term and Long-term perspective. This was due to increased revenues in the future perspectives, which is motivated by higher prices/value of energy from waste. Although fuel and energy prices are expected to increase in the future, capital and operational expenditure are expected to remain close to present levels. With careful consideration for the cost parameters used in this work, some important aspects may be delineated below on the net system results:

- System variants with central sorting tended to have a higher net system cost compared to system variants with direct incineration, except for CS-Biodry variants in the costing alternative where all RDF produced in the system is utilized for heat production. In fact, this variant under these conditions achieved a reduction in system costs compared to the incineration variants.
- There was a high increase in costs from System 0 to System 2, 3 and 5, which was associated to the introduction of kerbside separate collection of biowaste and recyclable materials.
- The net system cost difference between variants with incineration and variants with central sorting decreased significantly between the Present and the Long-term time perspective, and this was due to the increasing value of flexible energy considered in this work.
- The costing alternative where the whole chain of energy production from biomethane was included (that is combustion of biomethane in a gas motor and sale of electricity and heat) appeared to incur higher costs than the costing alternative which considers only the direct sale of biomethane.
- The costing alternative where RDF was considered used entirely for district heating production displayed a substantial net system cost decrease compared to the costing alternatives where RDF is used in CHP production. The cost difference is explained by (1) the lower processing costs of an RDF boiler compared to an CHP incineration plant, and (2) the higher energy efficiency considered for the RDF boiler (97 %) compared to the CHP (overall 84 %).
- In the Long-term time perspective, and the costing alternative with biomethane sale and RDF used in for heat only, CS variants displayed the same system costs as WtE variants, thus completely overcoming cost differences visible in the Present and Mid-term. This was connected especially to the effect of revenues from biomethane sale, at the estimated value of synthetic gas (which was substantially higher than the value of natural gas).

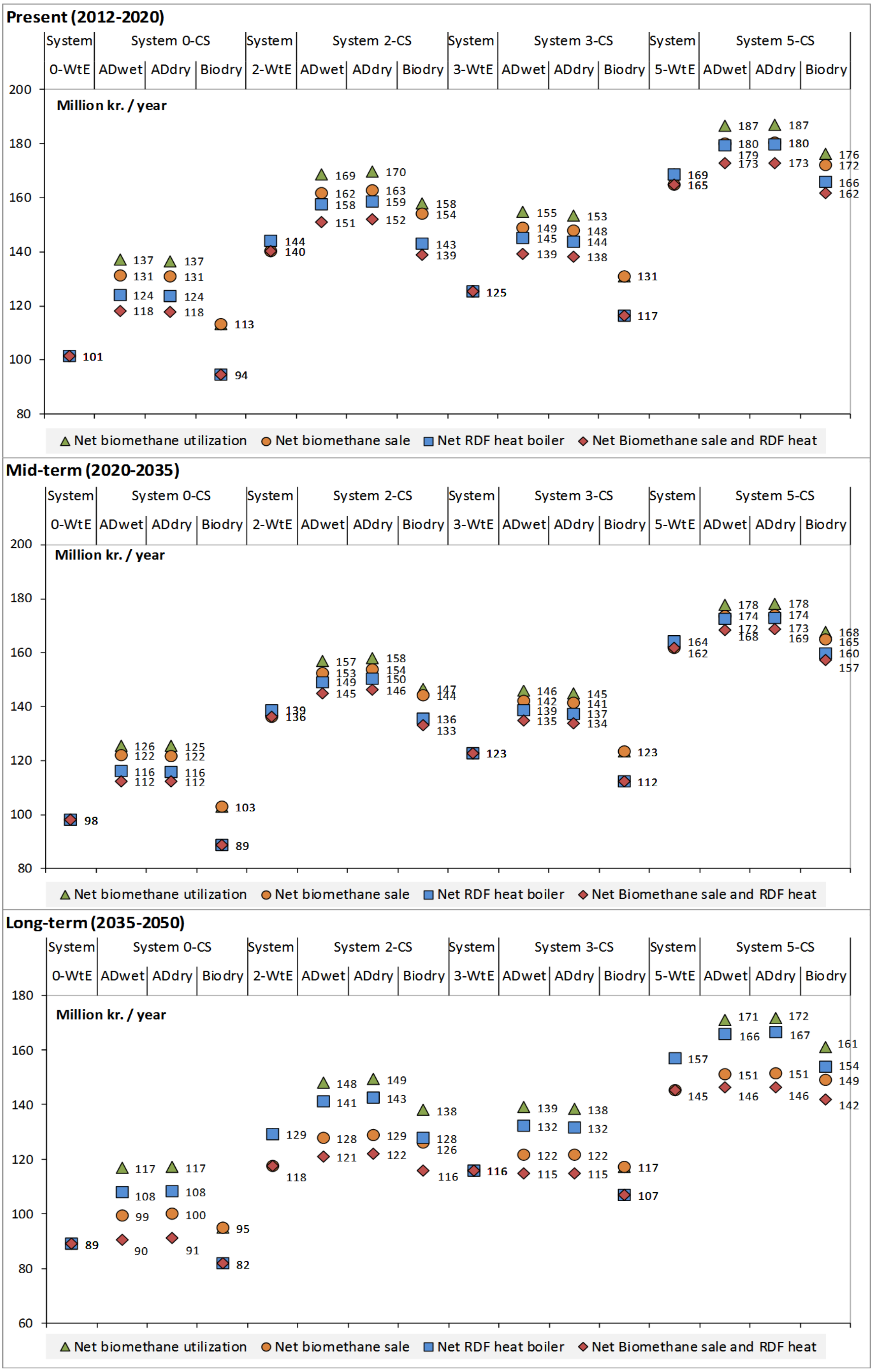


Figure 34: Overview of results from the economic analysis; net system costs

Regarding the individual contribution of different system components (Figure 35), the following can be commented:

- The sum of total costs for the existing system that treated 157,000 tonnes of waste in the region in 2013 was estimated at 190 million kr./year, while the total revenues from materials and energy sales were estimated to 90 million kr./year.
- Collection costs made up the largest share of cost in all systems. Costs associated with collection amounted to 96 million kr./year in System 0 (existing collection in the region), 147 million kr./year in System 2 (addition of biowaste collection), 121 million kr./year in System 3 (addition of the dual-stream) and 173 million kr./year in System 5 (addition of both biowaste and dual-stream collection).
- Total system costs increased from 190 million kr./year (0-WtE) to a maximum of 283 million kr./year in system 5-CS-ADwet, while total revenues increase to a maximum of 114 million kr./year in the Long-term time perspective. Total costs and revenues for all systems, in the four costing alternatives are compiled in a table in Appendix 3.
- In all systems, the variants CS-ADwet and CS-ADdry incurred the highest costs. The cost breakdown shows that this was connected to dewatering of digestate and/or incineration of digestate, which both have large unit costs.
- CS-Biodry variants achieved costs and revenues similar to the WtE variants. With RDF directed to CHP use, net system costs were slightly higher (4-7 million kr./year) than WtE, while with RDF directed to a RDF heat boiler, net system costs were lower (3-9 million kr./year) compared to WtE.
- The change from existing collection schemes for recyclable materials to the uniform dual-stream resulted in a near doubling of revenues from material sales (from 25 to 46 million kr./year). In addition, materials recovered directly from residual waste contributed between 7 and 12 million kr./year. Material prices are expected to increase in the future, however, this was not included in the analysis, and therefore revenues from material sales were likely underestimated.
- The costs to sort the dual-stream were calculated based on transport and processing in a large plant in Jutland, however, both mixed streams could be sorted locally, which would reduce costs while keeping all the revenues from material sales in the region.

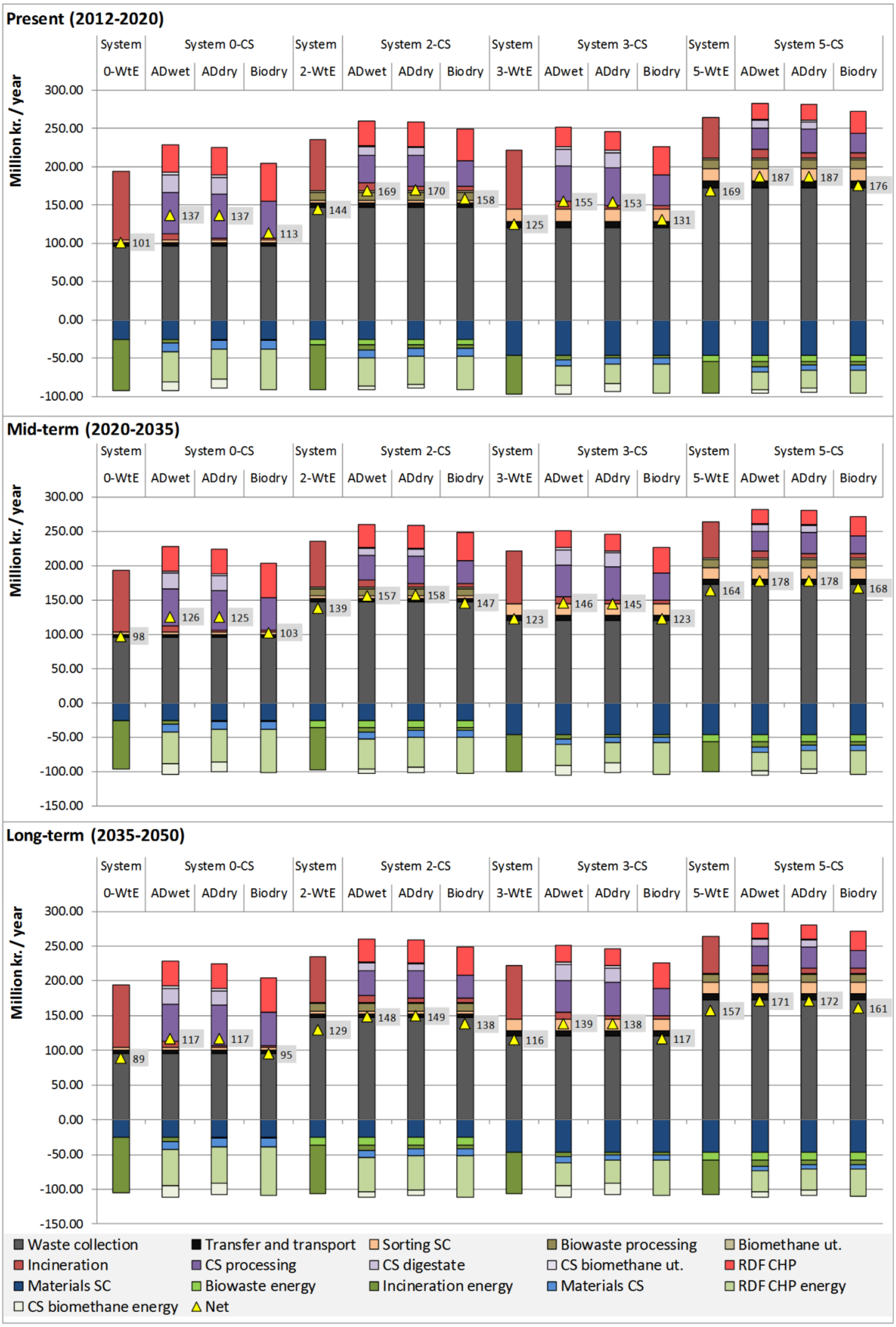


Figure 35: Breakdown of system costs, in the costing alternative with biomethane utilization for electricity and heat production and RDF CHP (figures for the three other alternatives are in the appendix 3)

3.2.2 The value of biowaste and RDF

Taking into consideration strictly the costs associated with the combustion of RDF and the revenues from the same of electricity and/or heat, a relative value of RDF to the CHP or district heating plant can be estimated. In a similar manner, the relative value for biogas produced by the bioslurry from biowaste can be estimated. The results per unit (tonne) are presented in Table 31.

RDF has higher LHV compared to residual waste, which means that more energy can be produced per unit weight. In the same way, bioslurry from biowaste has a higher CH_4 potential than for example manure, which means that more biomethane can be produced.

In the case of RDF we found that its relative value fluctuated a lot (depending on its average LHV) and increased substantially from the Present to the Mid-term and finally to Long-term. At the same time RDF value was much higher when used in a district heating boiler compared to a waste CHP. The reasons for this were explained Section 3.2.1.

In the case of bioslurry, its relative value was typically much lower than that of RDF, nevertheless, it still showed a potential value in the majority of cases. Its relative value was negative in the Present time perspective, with the costing alternative considering sale of electricity and heat. Its maximum value was achieved in the Long-term perspective, in the costing perspective with sale of biomethane (215 kr./tonne). On average, around 50 Nm^3 CH_4 are produced per tonne bioslurry, which would put the maximum value of bioslurry at 4.3 kr./Nm^3.

Table 31: Relative value of RDF and bioslurry (negative numbers indicate a negative value)

	Value of RDF		Value of bioslurry (biowaste)	
	CHP	Heat boiler	Sale of energy	Sale of biomethane
Present (2012-2020)	kr./tonne	kr./tonne	kr./tonne	kr./tonne
0-CS-ADwet/ADdry	70	358		
0-CS-Biodry	47	349		
2-WtE			-9	47
2-CS-ADwet/ADdry	105	373	-9	47
2-CS-Biodry	64	356	-9	47
3-CS-ADwet/ADdry	29	341		
3-CS-Biodry	28	340		
5-WtE			-9	47
5-CS-ADwet/ADdry	76	361	-9	47
5-CS-Biodry	53	351	-9	47
Mid-Term (2020-2035)	kr./tonne	kr./tonne	kr./tonne	kr./tonne
0-CS-ADwet/ADdry	240	451		
0-CS-Biodry	212	439		
2-WtE			25	60
2-CS-ADwet/ADdry	281	469	25	60
2-CS-Biodry	232	447	25	60
3-CS-ADwet/ADdry	191	429		
3-CS-Biodry	189	428		
5-WtE			25	60
5-CS-ADwet/ADdry	247	454	25	60
5-CS-Biodry	219	442	25	60
Long-term (2035-2050)	kr./tonne	kr./tonne	kr./tonne	kr./tonne
0-CS-ADwet/ADdry	367	561		
0-CS-Biodry	336	546		
2-WtE			47	215
2-CS-ADwet/ADdry	414	584	47	215
2-CS-Biodry	359	557	47	215
3-CS-ADwet/ADdry	312	535		
3-CS-Biodry	310	534		
5-WtE			47	215
5-CS-ADwet/ADdry	375	565	47	215
5-CS-Biodry	344	550	47	215

3.3 Conclusions to Part 3

The budget-based economic analysis performed and reported in this section revealed that the economic performance of the existing waste management systems in the region and modelled alternative systems was dependent to a relatively high degree on the background conditions in Denmark and their predicted future development.

In general, the analysis showed that if the value of functional outputs will increase in the future, in connexion with the predicted increase of fuel and energy prices, the total costs for the waste sector will likely decrease. In this analysis the net system costs decreased between the Present and the Long-term time perspective by a maximum of 20 %. The total decrease, in every case, was larger for systems which produced flexible electricity and heat.

Collection of waste from households was the most costly part of the systems, in every case contributing with more than 50% of total system costs. There are probably avenues for optimization and therefore cost reduction, therefore the collection costs in this work could be slightly overestimated. Collection of the dual-stream throughout the region was more cost effective than biowaste collection.

The system CS-Biodry, where all residual waste is converted to storable RDF, was indicated as the least expensive in all three time periods, possibly even achieving savings compared to today's system in the region.

Both RDF and bioslurry produced from biowaste have a potential relative value, when considering their further use to produce district heating and biomethane. This relative value increases significantly in the future due to the possibility to use RDF and biomethane to produce flexible electricity and heat.

Bibliography

ALLEGRINI, E., MARESCA, A., OLSSON, M. E., HOLTZE, M. S., BOLDRIN, A. & ASTRUP, T. F. 2014. Quantification of the resource recovery potential of municipal solid waste incineration bottom ashes. *Waste Management,* 34**,** 1627-1636.

BANG, C., VITINA, A., GREGG, J. S. & LINDBOE, H. H. 2013. Analysis of biomass prices, future Danish prices for straw, wood chips and wood pellets "Final Report". Copenhagen, Denmark: Ea Energy Analyses.

BEKON 2015. Energy for the future: Dry fermentation, Brochure. München, Germany: BEKON.

BERNSTAD, A. & JANSEN, J. L. 2011. A life cycle approach to the management of household food waste - A Swedish full-scale case study. *Waste Management,* 31**,** 1879-1896.

BERNSTAD, A., MALMQUIST, L., TRUEDSSON, C. & JANSEN, J. L. 2013. Need for improvements in physical pretreatment of source-separated household food waste. *Waste Management,* 33**,** 746-754.

BIGANZOLI, L., GORLA, L., NESSI, S. & GROSSO, M. 2012. Volatilisation and oxidation of aluminium scraps fed into incineration furnaces. *Waste Management,* 32**,** 2266-72.

BIRKEMOSE, T., HJORT-GREGERSEN, K. & STEFANEK, K. 2013. Biomasse til biogasanlæg i Danmark - på kort og langt sigt [Biomass to biogasfacilities in Denmark - in short and long term perspective]. ArgoTech, Instetut for Jordbrugs- og Fødevareinnovation.

CHRISTIANI, J. 2009. Möglichkeiten und Randbedinungen einer Wertstoffrück-gewinnung aus Abfallgemischen.

CIMPAN, C., MAUL, A., JANSEN, M., PRETZ, T. & WENZEL, H. 2015a. Central sorting and recovery of MSW recyclable materials: A review of technological state-of-the-art, cases, practice and implications for materials recycling. *Journal of Environmental Management,* 156**,** 181-199.

CIMPAN, C., ROTHMANN, M., HAMELIN, L. & WENZEL, H. 2015b. Towards increased recycling of household waste: Documenting cascading effects and material efficiency of commingled recyclables and biowaste collection. *Journal of Environmental Management,* 157**,** 69-83.

DAHLEN, L. & LAGERKVIST, A. 2010. Evaluation of recycling programmes in household waste collection systems. *Waste Manag Res,* 28**,** 577-86.

DAHLÉN, L., VUKICEVIC, S., MEIJER, J.-E. & LAGERKVIST, A. 2007. Comparison of different collection systems for sorted household waste in Sweden. *Waste Management,* 27**,** 1298-1305.

DAKOFA. 2014. *Nyt om kildesortering versus central sortering i etageboliger - og generelt!* [Online]. Available: https://www.dakofa.dk/element/nyt-om-kildesortering-versus-central-sortering-i-etageboliger-og-generelt/.

DAMGAARD, A., LARSEN, A. W. & CHRISTENSEN, T. H. 2009. Recycling of metals: accounting of greenhouse gases and global warming contributions. *Waste Management & Research Waste Management & Research,* 27**,** 773-780.

DANISH MINISTRY OF FINANCE 2013. Faktaark - Ny og lavere samfundsøkonomisk diskonteringsrente [Fact Sheet - New and lower socio-economic discounting rate (in Danish)]. Copenhagen, Denmark: Finansministeriet - Danish Ministry of Finance.

DANSK AFFALD 2014. Rapport på projekt SAGA madaffald - 01. november 2012 – 28. februar 2013 [Main report for the Project SAGA food waste (in Danish)]. Vojens, Denmank.

DANSK AFFALD A/S 2013. Miljø- og arbejdsmiljøredegørelse 2012 [Environmental and workenvrionmental report 2012]. Denmark: Dansk Affald A/S.

DANSK AFFALDSFORENING 2013. Danskernes affaldshåndtering, - holdninger og - værdier [The Danes waste management, attitude and values].

DANSK AFFALDSFORENING, DI & ENERGI, D. 2013. BEATE Benchmarking af affaldssektoren 2013 (data fra 2012) Forbrænding. *Miljøstyrelsen*.

DAVIDSSON, Å., GRUVBERGER, C., CHRISTENSEN, T. H., HANSEN, T. L. & JANSEN, J. L. C. 2007. Methane yield in source-sorted organic fraction of municipal solid waste. *Waste Management,* 27**,** 406-414.

DEA 2014. Forudsætninger for samfundsøkonomiske analyser på energiområdet [Assumptions of socio-economic analyzes in the energy sector (in Danish)]. Copenhagen, Denmark: Danish Energy Agency.

DEA & ENERGINET 2012. Technology Data for Energy Plants: Generation of Electricity and District Heating, Energy Storage and Energy Carrier Generation and Conversion (updates made October 2013, January 2014 and March 2015). Copenhagen, Denmark: Danish Energy Agency.

DET ØKONOMISKE RÅD 2014. Diskussionsoplæg, Omkostninger ved BE-mål, Ressourcestrategi, Invasive arter, Rekreative værdier, Kollektiv trafik.

DONG 2012. Haderslev Kraftvarmevaerk - Miljøregnskab 2012 [Haderslev CHP plant - Environmental statement (in Danish)]. Frederecia, Denmark: DONG energy.

EA ENERGIANALYSE 2014. Anvendelse af biogas til el- og varmeproduktion [The use of biogas for electricity and heat (in Danish)]. Copenhagen, Denmark: Danish Energy Agency - the Biogas Taskforce.

ENERGISTYRELSEN 2014. Biogas i Danmark - status, barrierer og perspektiver [Biogas in Denmark - status, barriers and perspectives].

EUROPEAN COMISSION 2008. Directive 2008/98/EC of the European parliament and of the Council of 19 November 2008 on waste and repealing certain Directives *Official Journal of the European Union*, 28 pages.

GRÜNEKLEE, C. E. 2002. Biologische Trocknung von Hausmüll mit dem Herhof Trockenstabilat-Verfahren – Biologische, chemische und physikalische Grundlagen [Biological drying of household waste with the Herhof Dry Stabilat process - Biological, Chemical and Physical basics (in German)]. *In:* THOMÉ-KOZMIENSKY, K. J. (ed.) *Ersatzbrennstoffe 2.* Neuruppin, Germany: TK Verlag Karl Thomé-Kozmiensky.

HAMELIN, L. 2013. *Carbon management and environmental consequences of agricultural biomass in a Danish Renewable Energy strategy.* Ph.D. thesis, University of Southern Denmark.

HAMELIN, L., NAROZNOVA, I. & WENZEL, H. 2014. Environmental consequences of different carbon alternatives for increased manure-based biogas. *Applied Energy,* 114**,** 774-782.

HAMELIN, L., WESNÆS, M., WENZEL, H. & PETERSEN, B. M. 2011. Environmental Consequences of Future Biogas Technologies Based on Separated Slurry. *Environmental Science & Technology,* 45**,** 5869-5877.

HANSEN, T. L., JANSEN, J. L. C., DAVIDSSON, A. & CHRISTENSEN, T. H. 2007. Effects of pre-treatment technologies on quantity and quality of source-sorted municipal organic waste for biogas recovery. *Waste Management,* 27**,** 398-405.

HYCKS, J., OBERENDER, A., HJELMAR, O., PEDERSEN, C., HANSEN, J. B. & HU, G. 2013. Undersøgelse af kommunejern fra genbrugspladser [Analysis of municipal Iron from recycling centres (in Danish)]. *Miljøprojekt nr. 1468.* Copenhagen, Denmark: Miljøstyrelsen.

INGENIØREN. 2013a. *Hver tredje forbrændingsanlæg fylder udenlandsk affald i ovnen [Every third incinerator fills foreign waste in the oven]* [Online]. Available: http://ing.dk/artikel/hvert-tredje-forbraendingsanlaeg-fylder-udenlandsk-affald-i-ovnen-136793.

INGENIØREN. 2013b. *Regeringens nye ressourcestrategi trækker affald ud af forbrændingsovenene [The government's new resource strategy pulls waste out of the incinerators]* [Online]. Available: http://ing.dk/artikel/regeringens-nye-ressourcestrategi-traekker-affald-ud-af-forbraendingsovnene-162452.

IPCC 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. *In:* STOCKER, T. F., QIN, D., PLATTNER, G.-K., TIGNOR, M., ALLEN, S. K., BOSCHUNG, J., NAUELS, A., XIA, Y., V., B. & MIDGLEY, P. M. (eds.). Cambridge, UK; New York: Published for the Intergovernmental Panel on Climate Change [by] Cambridge University Press.

JACOBSEN, B. H., LAUGESEN, F. M., DUBGAARD, A. & BOJESEN, M. 2013. Biogasproduktion i Danmark – Vurderinger af drifts- og samfundsøkonomi [Biogas production in Denmark - Ratings of operation and economy (in Danish)]. Copenhagen University, Department of Food and Resource Economics.

JAKOBSEN, J. B., KIRKEBY, J., MALMGREN-HANSEN, B., TØNNING, K. & NILSSON, N. H. 2014. Automatisk affaldssortering teknologier og danske udviklings- og produktions kompetencer [Automatic waste separation technologies and Danish engineering and manufacturing competences (in Danish)]. *Miljøprojekt nr. 1559.* Copenhagen, Denmark: Miljøstyrelsen.

KARAGIANNIDIS, A., BILITEWSKI, B. & TCHOBANOGLOUS, G. 2008. Waste to Energy: On Thermal Treatment and Energetic Utilization of Solid Wastes. *In:* GOLUSH, T. V. (ed.) *Waste Management Research Trends.* United States: Nova Science Publishers.

LARSEN, A. W., PETERSEN, C. & CHRISTENSEN, T. H. 2011. Bulky waste quantities and treatment methods in Denmark. *Waste Management & Research*.

LARSEN, A. W., VRGOC, M., CHRISTENSEN, T. H. & LIEBERKNECHT, P. 2009. Diesel consumption in waste collection and transport and its environmental significance. *Waste Management and Research,* 27**,** 652-659.

LIGHART, T. N., VALKERING, M. S. & ANSEMS, A. M. M. 2013. Life Cycle Assessment of beverage carton collection systems. Earth, Environmental and Life Sciences, The Netherlands.

LORENTZEN, B. W., LARSEN, B. & LARSEN, P. F. 2013. Oparbejdning af organisk affald til Biopulp [Processing of organic waste to Biopulp - in Danish], Miljøprojekt nr. 1506. Copenhagen, Denmark: Miljøstyrelsen.

LUIJSTERBURG, B. & GOOSSENS, H. 2014. Assessment of plastic packaging waste; Material origin, methods, properties. *Resources, Conservation and Recycling***,** 88-97.

MERRILD, H., DAMGAARD, A. & CHRISTENSEN, T. H. 2009. Recycling of paper: accounting of greenhouse gases and global warming contributions. *Waste Management & Research,* 27**,** 746-753.

MILJØSTYRELSEN 2014. Danmark uden affald, Ressourceplan for affaldshåndtering 2013-2018. *In:* MILJØMINISTERIET (ed.) *Vejledning fra Miljøstyrelsen nr. 4, 2014.* København.

MØLLER, J., M.B., J., KROMANN, M., NEIDEL, T. L. & JAKOBSEN, J. B. 2013. Miljø- og samfundsøkonomisk vurdering af muligheder for øget genanvendelse af papir, pap, plast, metal og organisk affald fra dagrenovation [Environmental and economic assessment of opportunities for increased recycling of paper, cardboard, plastic, metal and organic waste from municipal waste (in Danish)]. *Miljøprojekt nr. 1458.* Copenhagen, Denmark: Miljøstyrelsen.

NAROZNOVA, I., MØLLER, J. & SCHEUTZ, C. 2013. Life Cycle Assessment of pretreatment technologies for anaerobic digestion of source-separated organic household waste. *Sardinia 2013, Fourteenth International Waste Management and Landfill Symposium, 30 September – 4 October.* S. Margherita di Pula, Cagliari, Italy: CISA Publisher.

NIRAS 2013. Kortlægning af indsamlings- og forbehandlingsmetoder for organisk affald [Mapping of collection and pre-treatment methods for organic waste]. Copenhagen, Denmark: RenoSam.

PETERSEN, C. 2011. Affaldsanalyse - Småt brændbart i Renders [Waste analysis - Small combustible waste in Renders municipality (in Danish)]. *Projekt nr.: A418.* Econet.

PETERSEN, C. & DOMELA, I. 2003. Sammensætning af dagrenovation og ordninger for hjemmekompostering [Composition of residual waste and schemes for home composting]. *Environmental projekt No. 868.* Ministry of Environment.

PETERSEN, C., KAYSEN, O., MANOKARAN, S., TØNNING, K. & HANSEN, T. 2014. Kortlægning af dagrenovation i Danmark - med fokus på etageboliger og madspild. Miljøstyrelsen.

REIMANN, D. O. 2009. CEWEP Energy Report II (status 2004-2007): Results of specific data for energy, R1 plant efficiency factor and net calorific value (NCV) for 231 European WtE plants. Bamberg, Germany: CEWEP.

REINHARD, J., WEIDEMA, B. & SCHMIDT, J. H. 2010. Identifying the marginal supply of wood pulp. Aalborg, Denmark: 2.-0 LCA consultants.

RENOSAM 2011. Benchmarking på affaldsområder for 2010 [Benchmarking in waste sectors for 2010 (in Danish)]. Copenhagen, Denmark: RenoSam.

RIBER, C., PETERSEN, C. & CHRISTENSEN, T. H. 2009. Chemical composition of material fractions in Danish household waste. *Waste Management* 29**,** 1251-7.

SVENDBORG KRAFTVARMEVÆRK 2014. Svendborg Kraftvarmeværk A/S - Grønt regnskab 2013 [Svendborg waste CHP - Environmental report 2013 (in Danish)]. Svendborg, Denmark.

SWISS CENTRE OF LIFE CYCLE INVENTORIES Ecoinvent Database.

TAS 2014. Trekantsområdets Affaldsselskab I/S - Miljøredegørelse 2013 [Environmental report 2013 (in Danish)]. Kolding, Denmark.

THE DANISH GOVERNMENT 2011. *Energistrategi 2050 : fra kul, olie og gas til grøn energi [Energy strategy 2050: from coal, oil and gas towards green energy],* Kbh., Ministry of Climate and Energy.

THE DANISH GOVERNMENT 2013. Danish Resource Strategy: Denmark without waste, Recycle more - incinerate less. *In:* THE DANISH MINISTRY OF ENVIRONMENT (ed.). Denmark: The Environmental Protection Agency.

TONINI, D., HAMELIN, L., WENZEL, H. & ASTRUP, T. 2012. Bioenergy Production from Perennial Energy Crops: A Consequential LCA of 12 Bioenergy Scenarios including Land Use Changes. *Environmental Science & Technology,* 46**,** 13521-13530.

TUNÅ, P., HULTEBERG, C., 2014. Woody biomass-based transportation fuels - A comparative techno-economic study. Fuel 117, 1020-1026.

VAN VELZEN, U. T., BROS-BROUWERS, H., GROOT, J., BING, X., JANSEN, M. & LUIJSTERBURG, B. 2013a. Scenario study on post-consumer plastic packaging waste recycling. The Netherlands: Wageningen UR Food & Biobased Research.

VAN VELZEN, U. T., BROUWER, T., KEIJSERS, E., PRETZ, T. & A. FEIL, M. J. 2013b. Pilot beverage cartons, extended technical report.

VATTENFALL 2013. Odense Kraftvarmeværk A/S - Grønt regnskab 2013 [Odense waste CHP - Environmental report 2013 (in Danish)]. Odense, Denmark.

VELIS, C. A., LONGHURST, P. J., DREW, G. H., SMITH, R. & POLLARD, S. J. T. 2009. Biodrying for mechanical-biological treatment of wastes: A review of process science and engineering. *Bioresource Technology,* 100**,** 2747-2761.

VRIES, W., REM, P. & BERKHOUT, P. ADR: A New Method For Dry Classification. ISWA International Conference 12-15 Oct. 2009, 2009 2009.

WENS, B., GILLNER, R., HORNSBY, K. & PRETZ, T. 2010. Environmental impacts of NF-metal recycling - MSW as a resource.

WENZEL, H., HØIBYE, L., GRANDAL, R. D., HAMELIN, L., BIRD, D. N. & OLESEN, A. S. 2014. Carbon footprint of bioeneergy pathways for the future Danish energy system - Main report. *Project No. A037857.* Copenhagen, Denmark: Danish Energy Agency.

Appendix 1: System process flow diagrams (PFD)

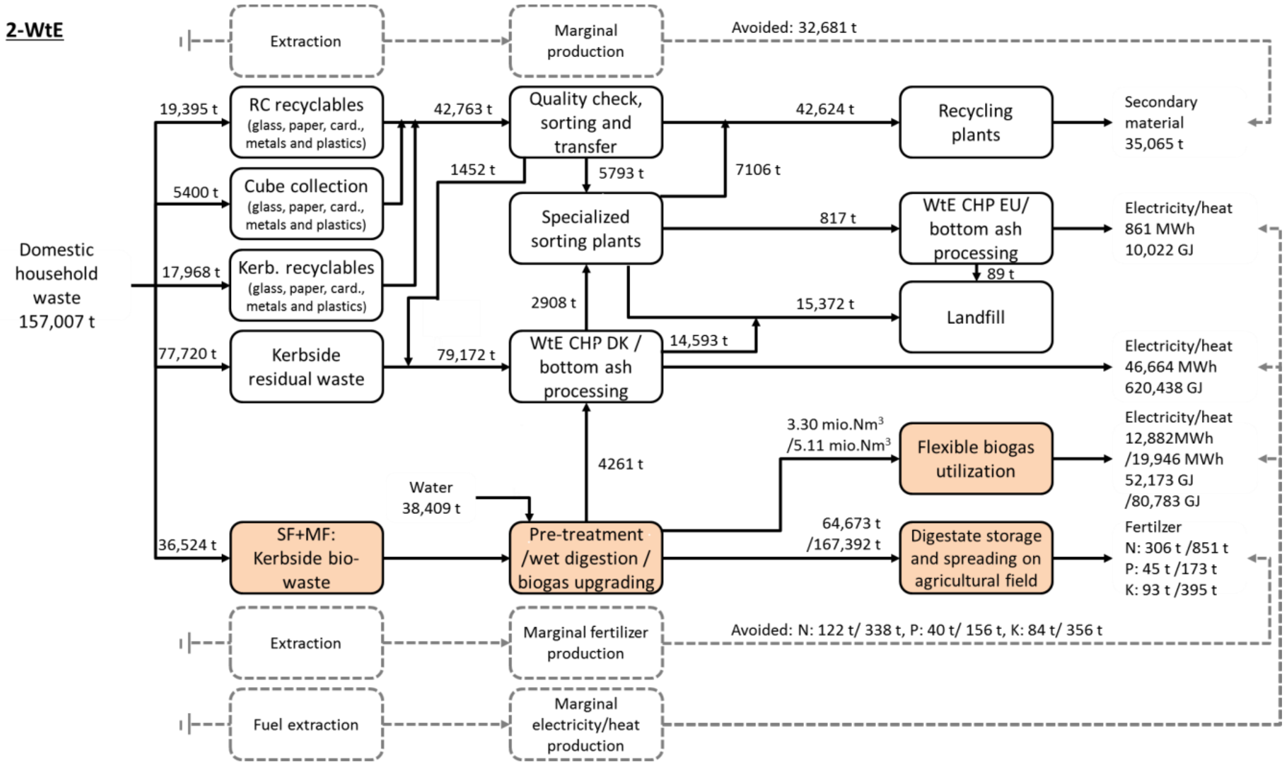


Figure 1: PFD for System 2-WtE

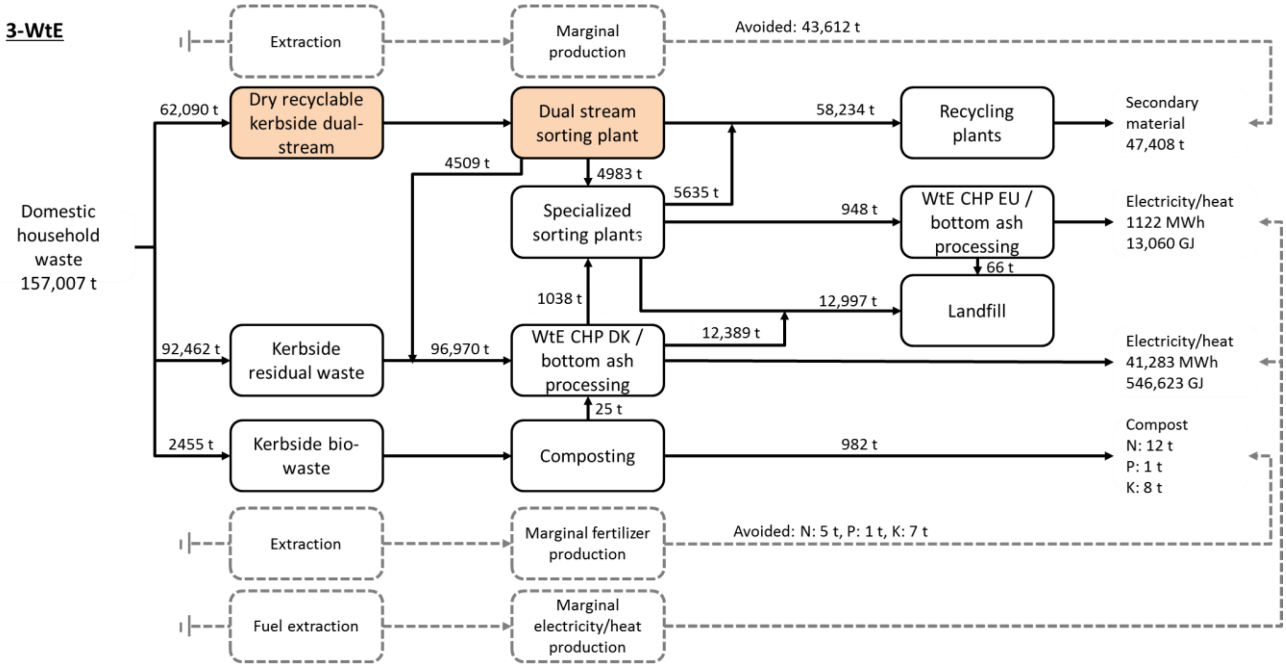


Figure 2: PFD for System 3-WtE

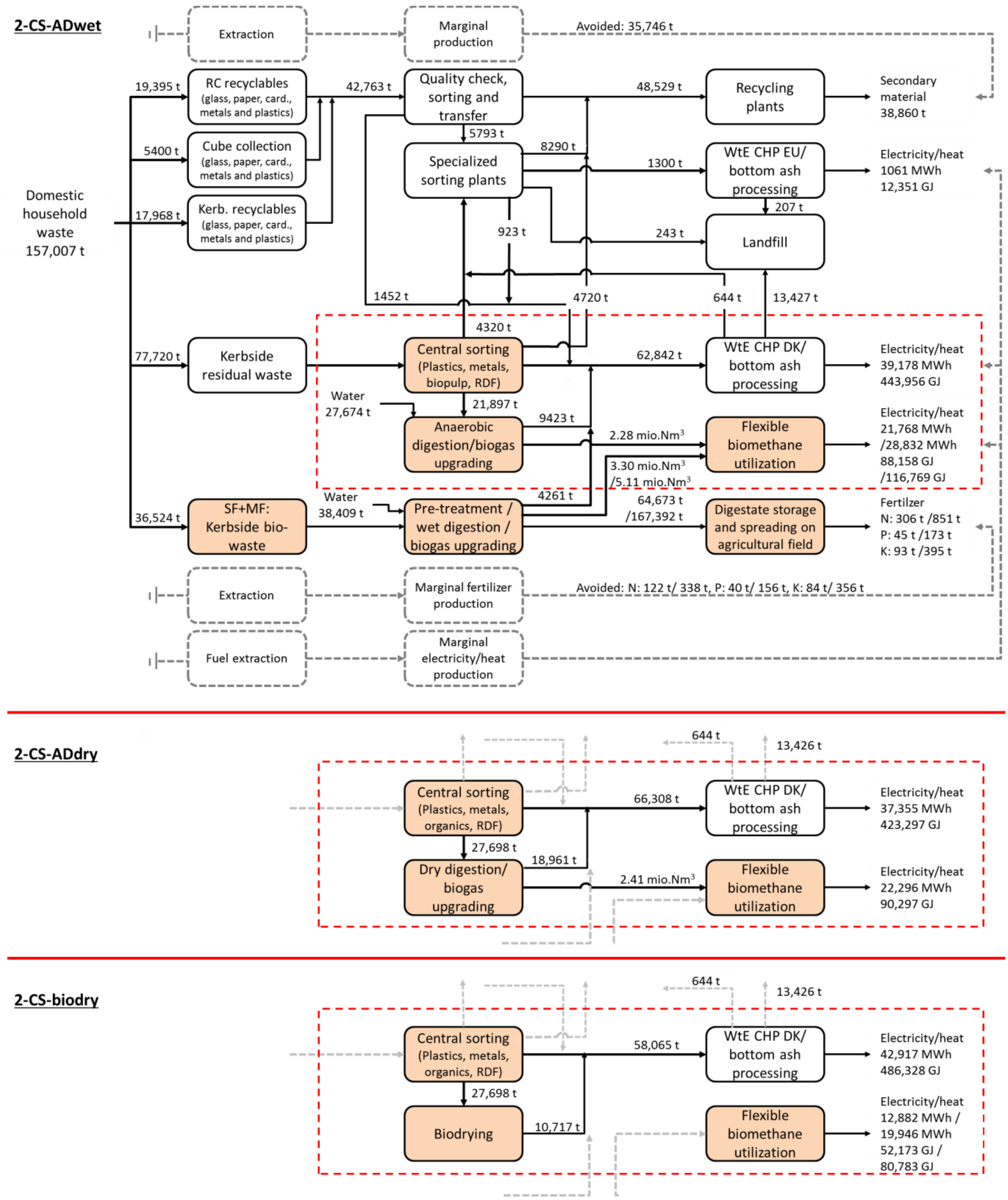


Figure 3: PFD for System 2-CS-ADwet/ADdry/Biodry

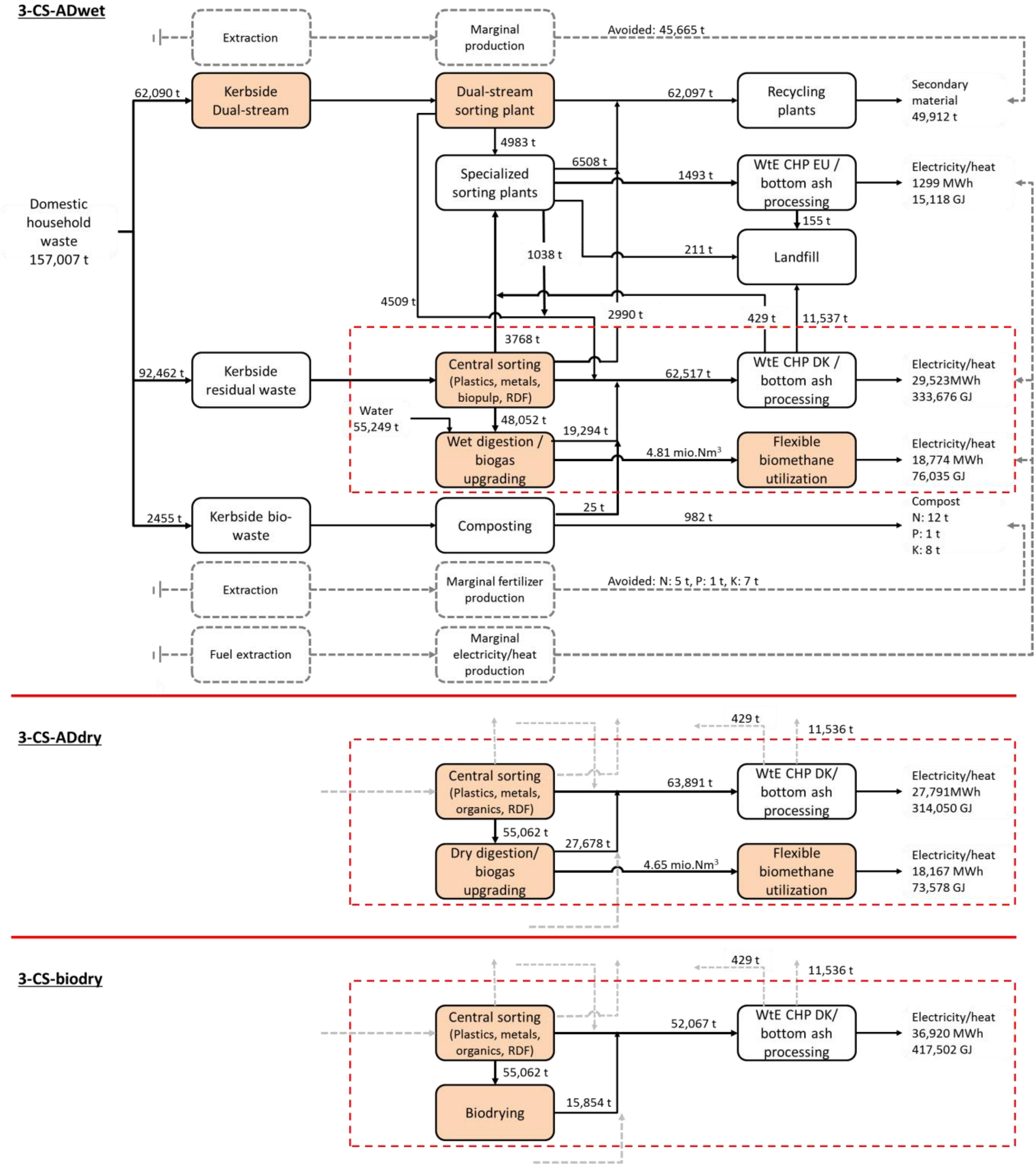


Figure 4: PFD for System 3-CS-ADwet/ADdry/Biodry

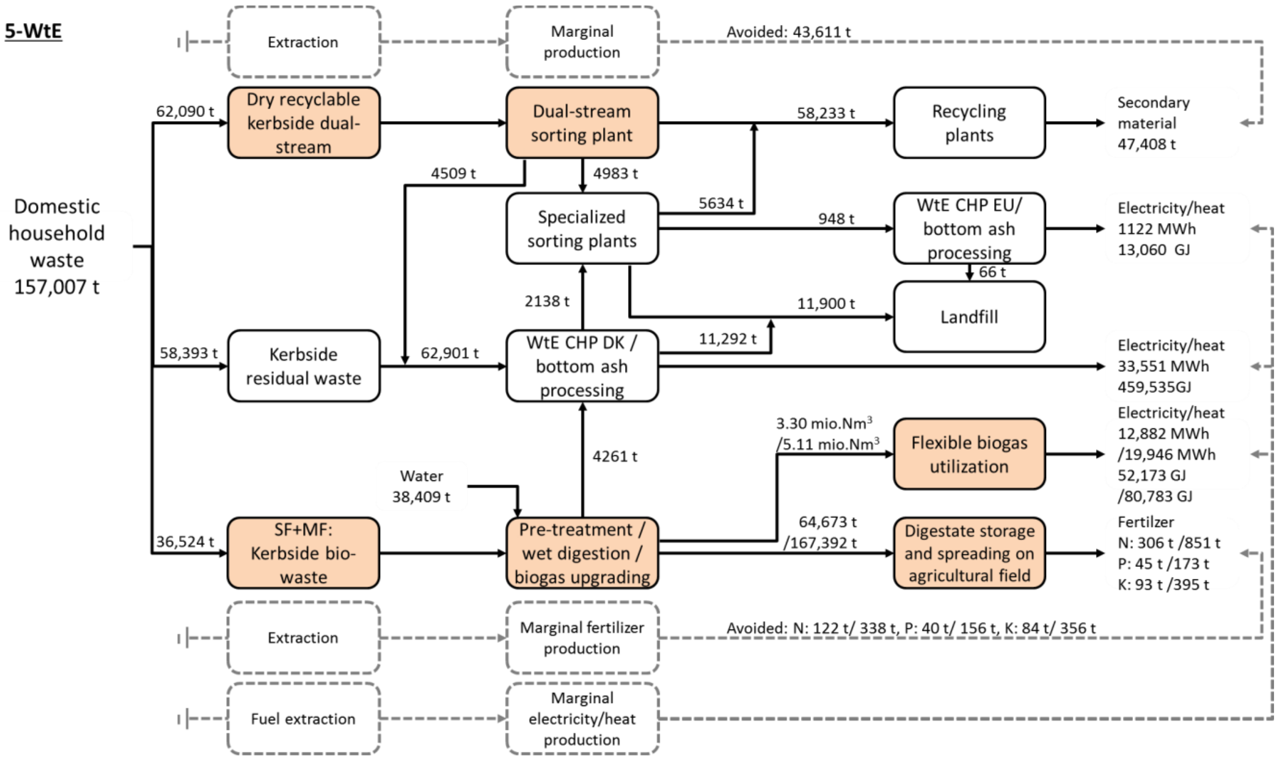


Figure 5: PFD for System 5-WtE

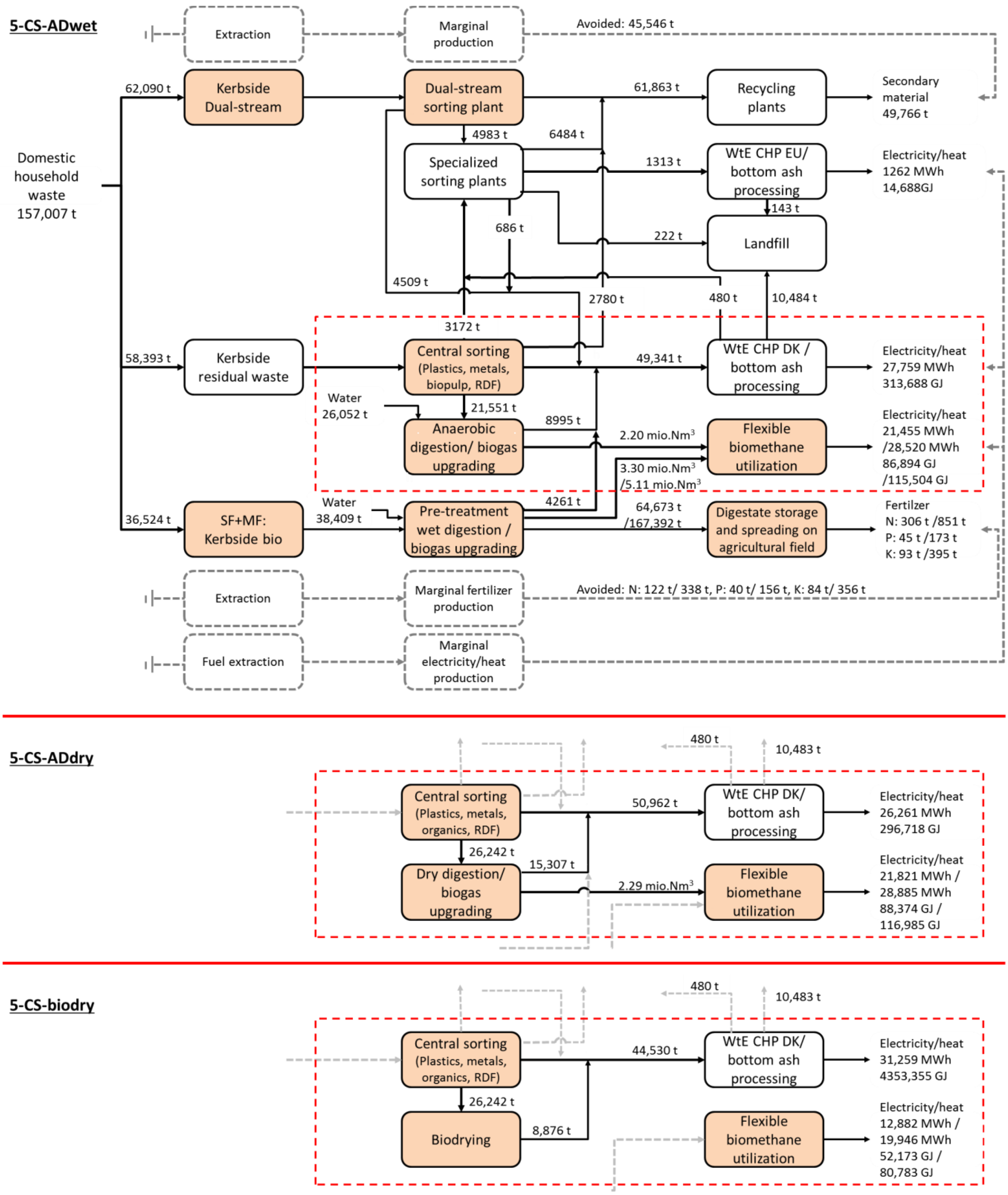


Figure 6: PFD for System 5-CS-ADwet/ADdry/Biodry

Appendix 2: Additional carbon footprint results

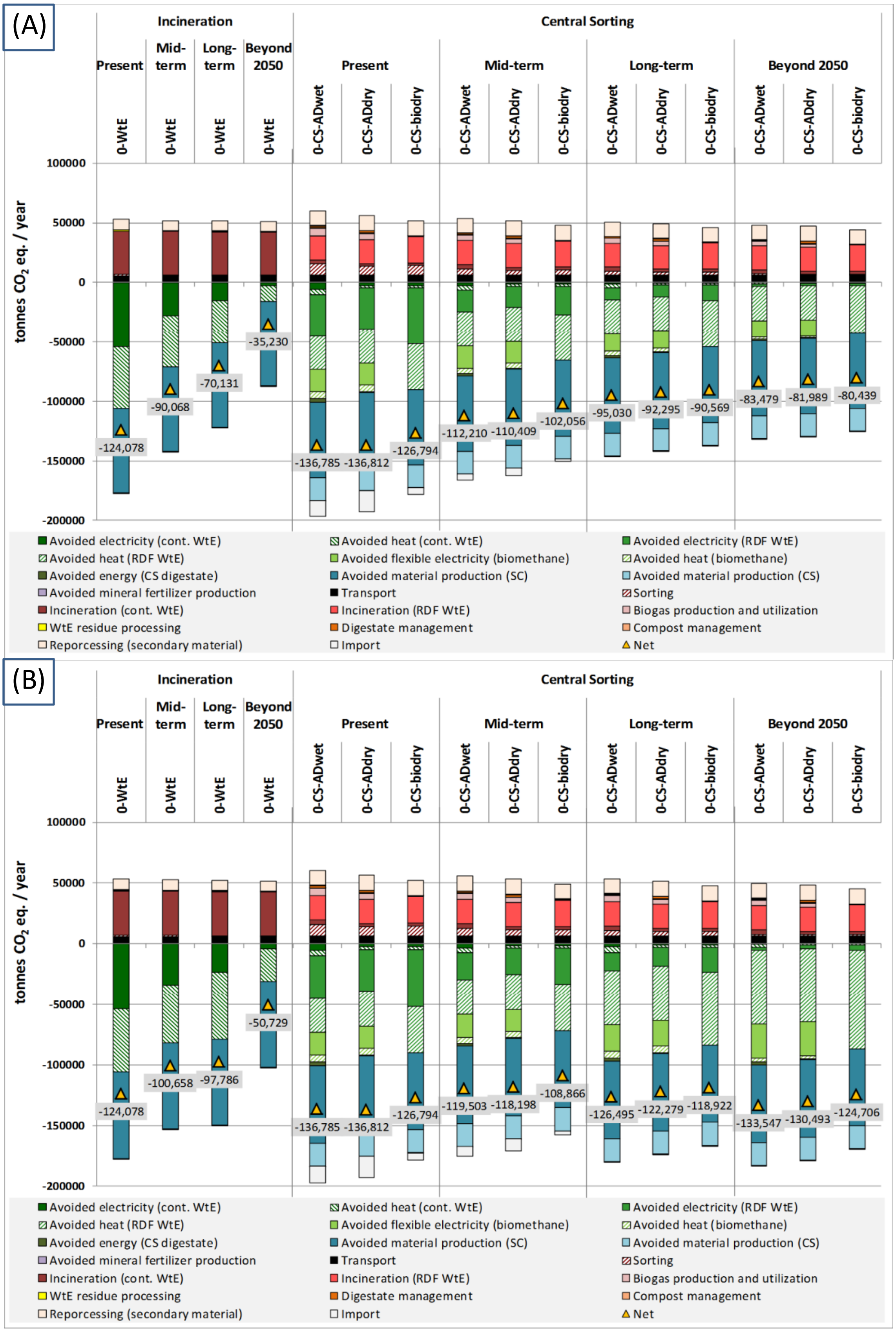
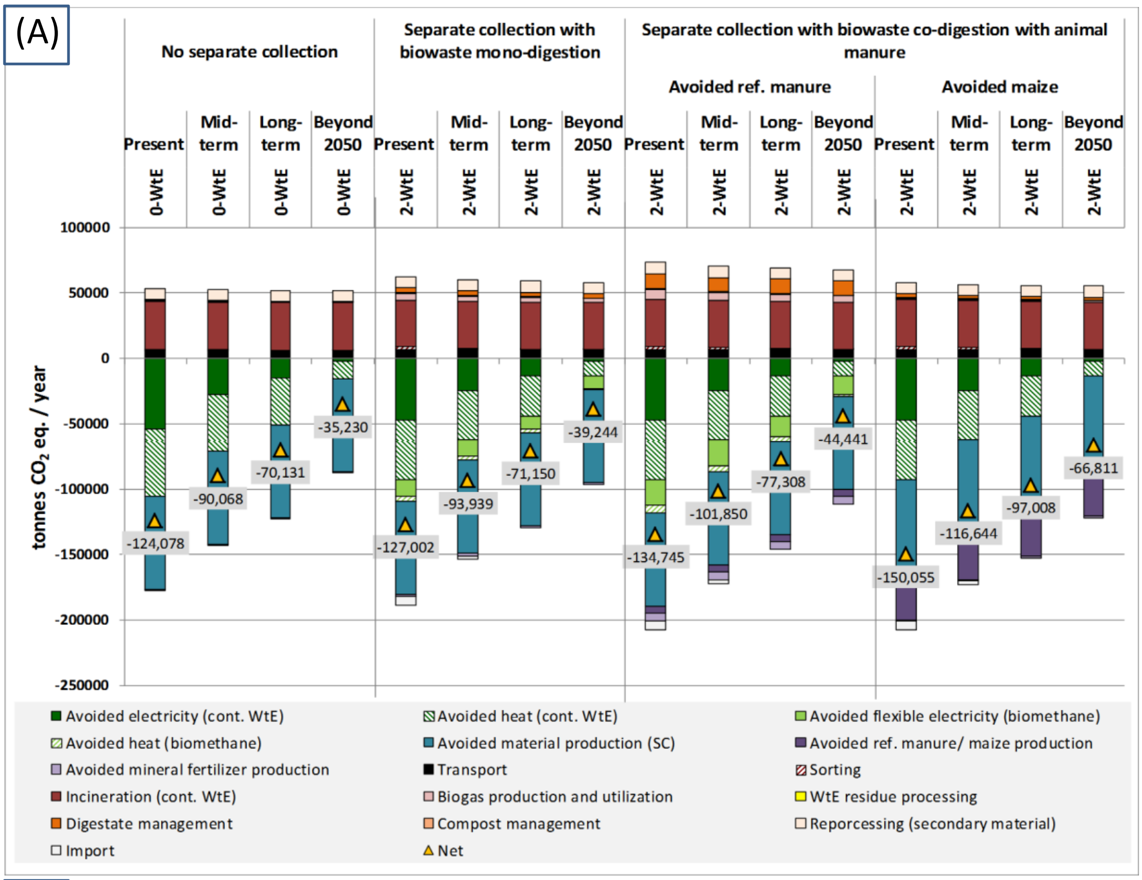


Figure 7: Dirty biomass marginal: System 0 (existing separate collection) with WtE or CS of residual waste, with biomass marginal amortization of 100 years (A) and 20 years (B).



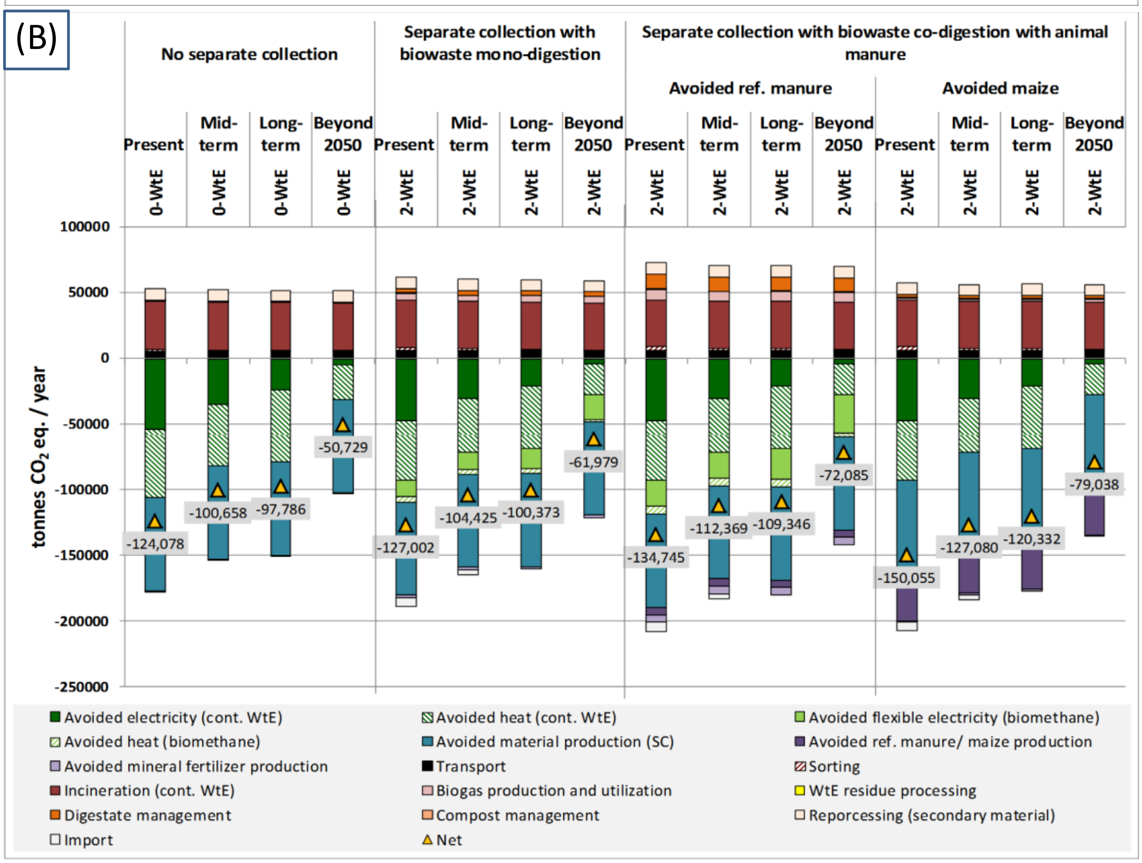
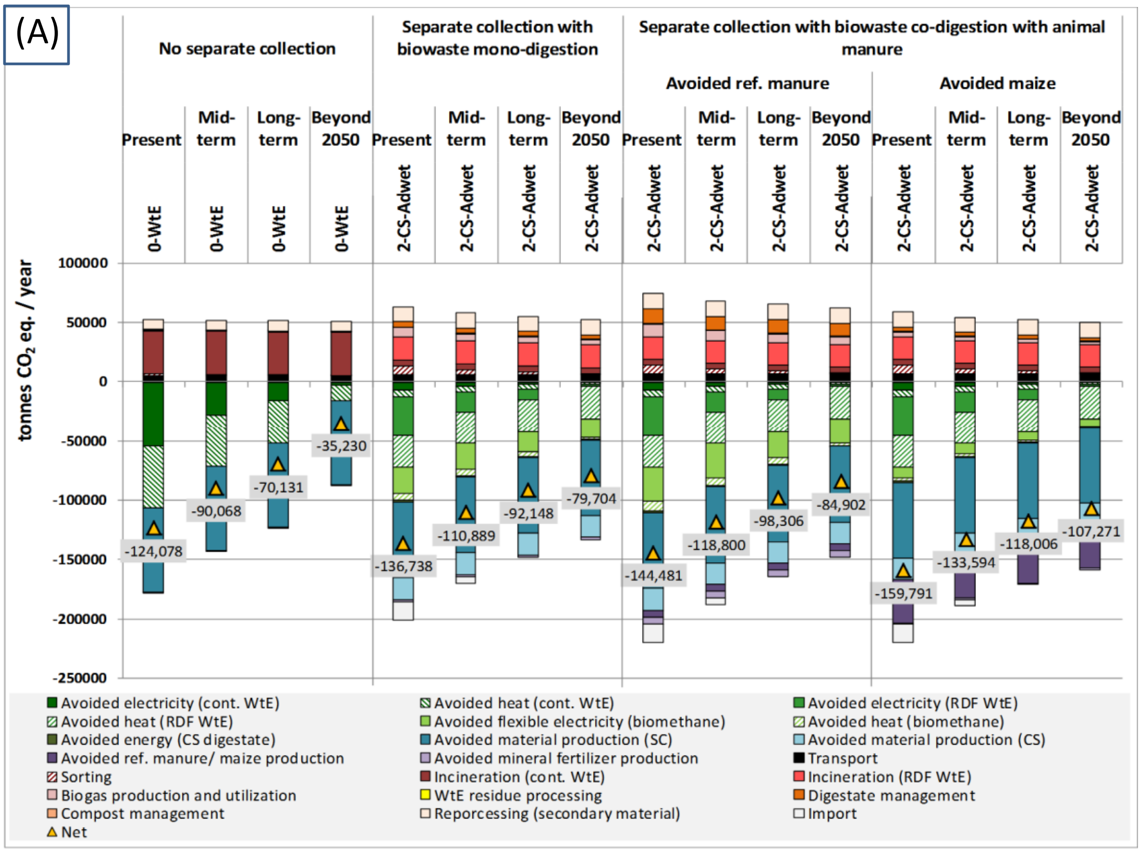


Figure 8: Dirty biomass marginal: System 0-WtE (no separate collection of biowaste) and 2-WtE (biowaste collection in both single and multi-family residences), with biomass marginal amortization of 100 years (A) and 20 years (B).



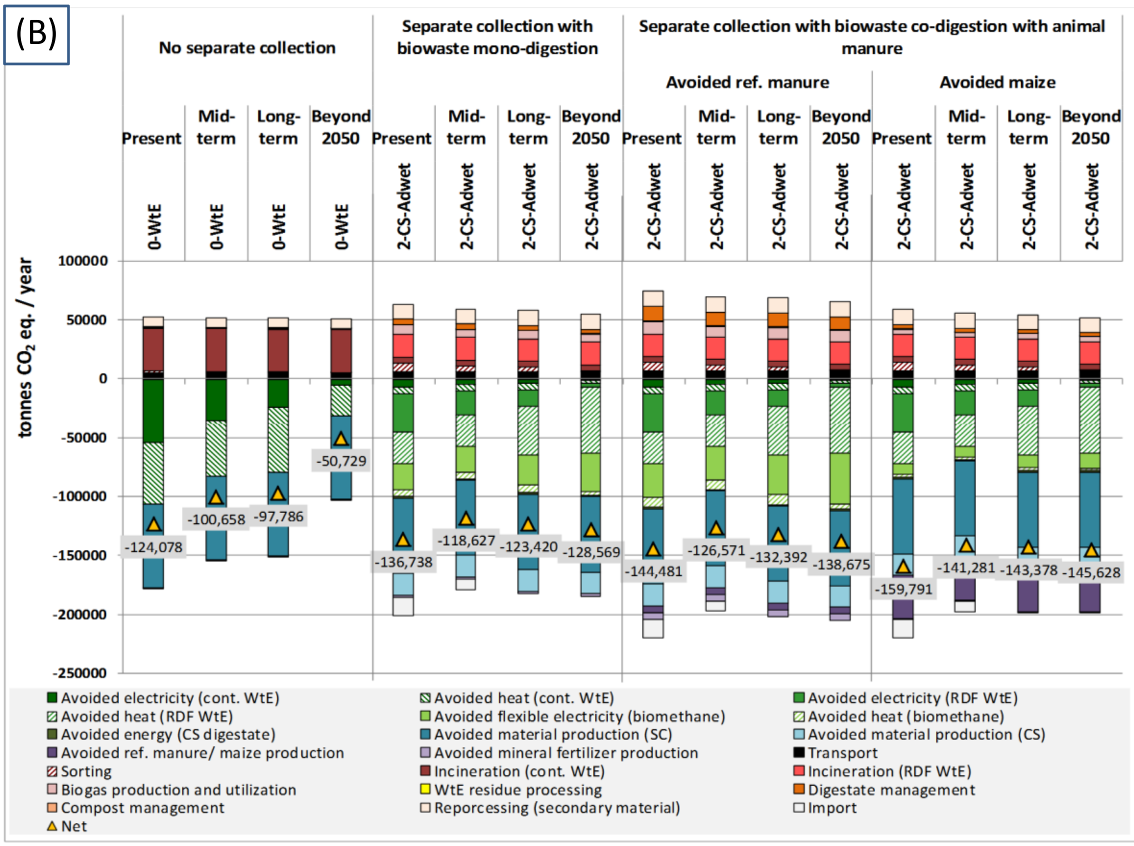


Figure 9: Dirty biomass marginal: System 0-WtE (no separate collection of biowaste) and 2-CS-ADwet (biowaste collection in both single and multi-family residences, central sorting and wet digestion of bio-concentrate), with biomass marginal amortization of 100 years (A) and 20 years (B).

Appendix 3: Additional economic analysis results

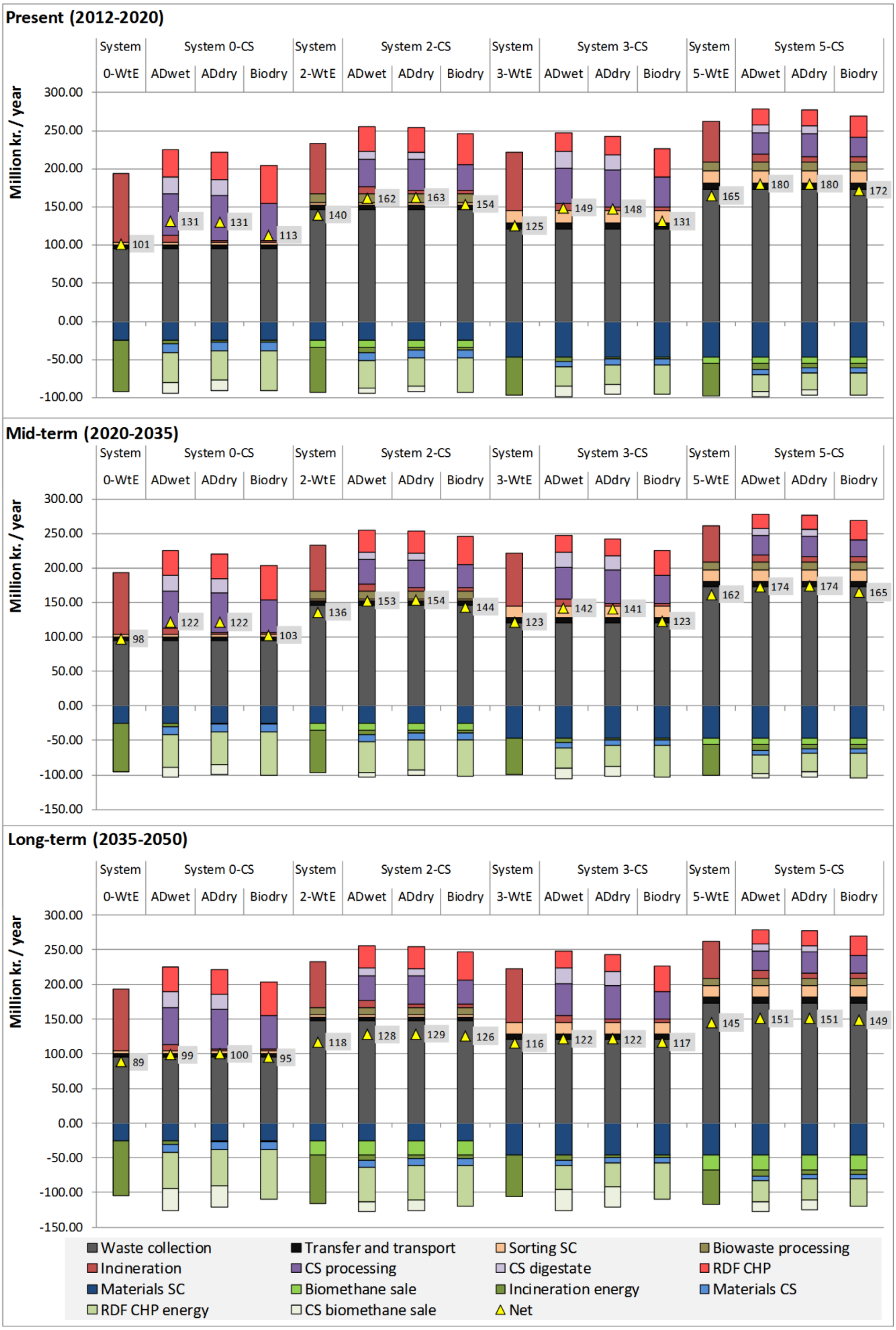


Figure 10: Breakdown of system costs, in the costing alternative with sale of biomethane and RDF CHP

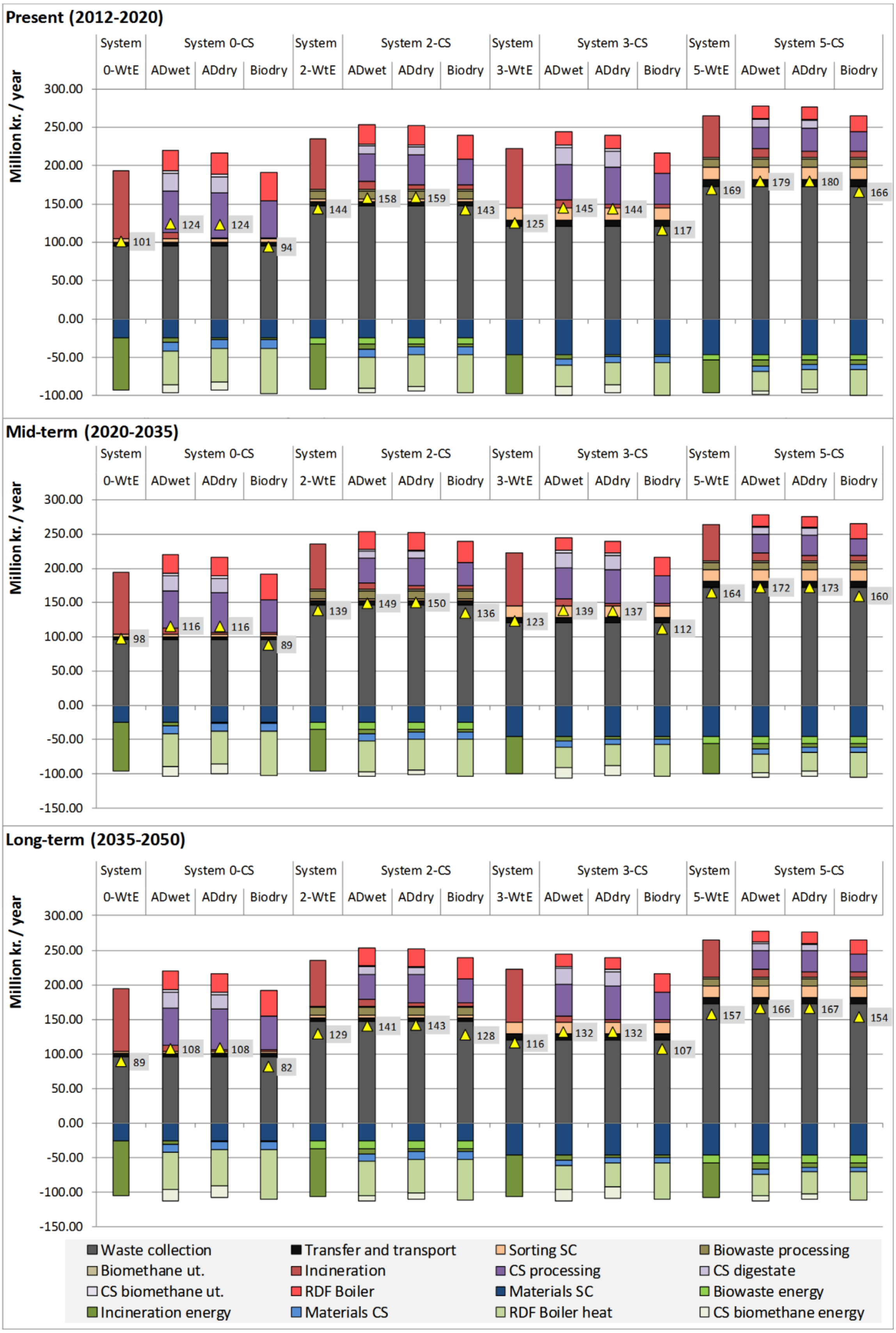


Figure 11: Breakdown of system costs, in the costing alternative with biomethane utilization for electricity and heat production and RDF heat only boiler

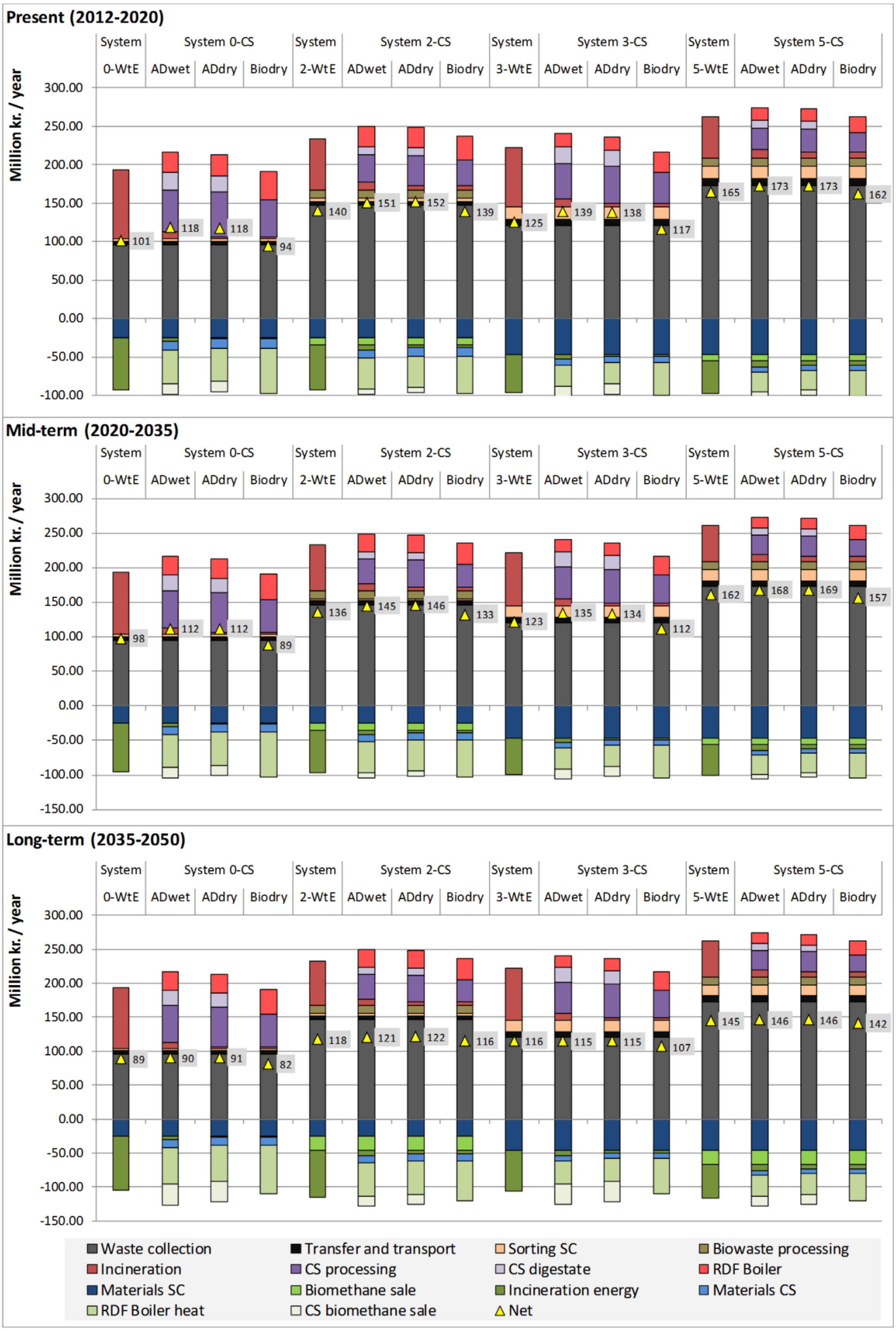


Figure 12: Breakdown of system costs, in the costing alternative with sale of biomethane and RDF heat boiler

Table 1: Total system costs, revenues and net system costs in the four costing alternatives for biomethane and RDF

		Biomethane utilization and RDF CHP			Biomethane sale and RDF CHP			Biomethane utilization RDF heat boiler			Biomethane sale and RDF heat boiler		
Present		Costs	Revenues	Net	Costs	Revenues	Net	Costs	Revenues	Net	Costs	Revenues	Net
System	0-WtE	193.8	-92.5	101.4	193.8	-92.5	101.4	193.8	-92.5	101.4	193.8	-92.5	101.4
System 0-CS	ADwet	228.8	-91.7	137.1	225.3	-94.1	131.2	220.4	-96.3	124.1	216.9	-98.6	118.2
	ADdry	224.7	-88.2	136.6	221.3	-90.5	130.9	216.3	-92.7	123.6	212.9	-95.0	117.8
	Biodry	204.1	-90.8	113.3	204.1	-90.8	113.3	191.4	-96.9	94.5	191.4	-96.9	94.5
System	2-WtE	235.4	-91.3	144.1	233.1	-92.9	140.2	235.4	-91.3	144.1	233.1	-92.9	140.2
System 2-CS	ADwet	259.7	-91.2	168.5	255.8	-93.9	161.8	253.1	-95.5	157.6	249.1	-98.2	150.9
	ADdry	258.7	-89.0	169.6	254.6	-91.8	162.8	252.0	-93.3	158.7	247.9	-96.0	151.9
	Biodry	248.9	-91.0	157.9	246.6	-92.6	153.9	239.1	-96.2	142.9	236.7	-97.8	139.0
System	3-WtE	222.1	-96.8	125.2	222.1	-96.8	125.2	222.1	-96.8	125.2	222.1	-96.8	125.2
System 3-CS	ADwet	251.0	-96.3	154.7	247.5	-98.6	148.9	244.3	-99.2	145.1	240.9	-101.6	139.3
	ADdry	246.3	-93.0	153.3	243.0	-95.3	147.7	239.7	-95.9	143.7	236.4	-98.2	138.2
	Biodry	226.4	-95.3	131.1	226.4	-95.3	131.1	216.3	-99.8	116.5	216.3	-99.8	116.5
System	5-WtE	264.4	-95.7	168.7	262.0	-97.3	164.8	264.4	-95.7	168.7	262.0	-97.3	164.8
System 5-CS	ADwet	282.6	-95.8	186.8	278.7	-98.5	180.2	277.8	-98.5	179.4	273.9	-101.1	172.8
	ADdry	281.0	-93.8	187.1	277.0	-96.5	180.4	276.2	-96.5	179.7	272.2	-99.2	173.0
	Biodry	271.7	-95.5	176.2	269.3	-97.1	172.2	264.7	-99.0	165.7	262.4	-100.6	161.8
Mid-term		Costs	Revenues	Net	Costs	Revenues	Net	Costs	Revenues	Net	Costs	Revenues	Net
System	0-WtE	193.8	-95.8	98.1	193.8	-95.8	98.1	193.8	-95.8	98.1	193.8	-95.8	98.1
System 0-CS	ADwet	228.8	-103.3	125.6	225.3	-103.4	121.9	220.4	-104.3	116.0	216.9	-104.5	112.4
	ADdry	224.7	-99.4	125.3	221.3	-99.6	121.8	216.3	-100.5	115.8	212.9	-100.6	112.2
	Biodry	204.1	-101.2	102.9	204.1	-101.2	102.9	191.4	-102.7	88.7	191.4	-102.7	88.7
System	2-WtE	235.4	-96.6	138.8	233.1	-96.7	136.3	235.4	-96.6	138.8	233.1	-96.7	136.3
System 2-CS	ADwet	259.7	-102.9	156.9	255.8	-103.1	152.7	253.1	-103.9	149.2	249.1	-104.1	145.0
	ADdry	258.7	-100.6	158.1	254.6	-100.8	153.8	252.0	-101.6	150.4	247.9	-101.8	146.1
	Biodry	248.9	-102.3	146.6	246.6	-102.4	144.1	239.1	-103.5	135.5	236.7	-103.7	133.1
System	3-WtE	222.1	-99.3	122.7	222.1	-99.3	122.7	222.1	-99.3	122.7	222.1	-99.3	122.7
System 3-CS	ADwet	251.0	-105.2	145.8	247.5	-105.3	142.2	244.3	-105.8	138.5	240.9	-106.0	134.9
	ADdry	246.3	-101.6	144.8	243.0	-101.7	141.3	239.7	-102.2	137.5	236.4	-102.4	134.0
	Biodry	226.4	-103.0	123.4	226.4	-103.0	123.4	216.3	-104.1	112.3	216.3	-104.1	112.3
System	5-WtE	264.4	-100.2	164.2	262.0	-100.3	161.7	264.4	-100.2	164.2	262.0	-100.3	161.7
System 5-CS	ADwet	282.6	-104.8	177.9	278.7	-105.0	173.7	277.8	-105.4	172.4	273.9	-105.6	168.3
	ADdry	281.0	-102.7	178.2	277.0	-102.9	174.1	276.2	-103.3	172.8	272.2	-103.5	168.6
	Biodry	271.7	-104.1	167.6	269.3	-104.2	165.1	264.7	-104.9	159.8	262.4	-105.0	157.3
Long-term		Costs	Revenues	Net	Costs	Revenues	Net	Costs	Revenues	Net	Costs	Revenues	Net
System	0-WtE	193.8	-104.8	89.1	193.8	-104.8	89.1	193.8	-104.8	89.1	193.8	-104.8	89.1
System 0-CS	ADwet	228.8	-112.0	116.8	225.3	-126.1	99.3	220.4	-112.3	108.0	216.9	-126.4	90.5
	ADdry	224.7	-107.6	117.1	221.3	-121.4	100.0	216.3	-107.9	108.3	212.9	-121.7	91.2
	Biodry	204.1	-109.2	94.9	204.1	-109.2	94.9	191.4	-109.6	81.8	191.4	-109.6	81.8
System	2-WtE	235.4	-106.1	129.4	233.1	-115.6	117.5	235.4	-106.1	129.4	233.1	-115.6	117.5
System 2-CS	ADwet	259.7	-111.8	148.0	255.8	-127.8	127.9	253.1	-112.1	141.0	249.1	-128.1	121.0
	ADdry	258.7	-109.2	149.5	254.6	-125.6	128.9	252.0	-109.5	142.5	247.9	-125.9	122.0
	Biodry	248.9	-110.9	138.0	246.6	-120.4	126.2	239.1	-111.3	127.8	236.7	-120.8	115.9
System	3-WtE	222.1	-106.1	116.0	222.1	-106.1	116.0	222.1	-106.1	116.0	222.1	-106.1	116.0
System 3-CS	ADwet	251.0	-112.0	139.0	247.5	-125.8	121.7	244.3	-112.1	132.2	240.9	-126.0	114.9
	ADdry	246.3	-107.9	138.4	243.0	-121.3	121.7	239.7	-108.1	131.6	236.4	-121.5	114.9
	Biodry	226.4	-109.1	117.3	226.4	-109.1	117.3	216.3	-109.4	106.9	216.3	-109.4	106.9
System	5-WtE	264.4	-107.4	157.0	262.0	-116.9	145.2	264.4	-107.4	157.0	262.0	-116.9	145.2
System 5-CS	ADwet	282.6	-111.7	170.9	278.7	-127.6	151.2	277.8	-111.9	165.9	273.9	-127.7	146.2
	ADdry	281.0	-109.4	171.5	277.0	-125.5	151.5	276.2	-109.6	166.6	272.2	-125.7	146.5
	Biodry	271.7	-110.7	161.0	269.3	-120.2	149.1	264.7	-111.0	153.7	262.4	-120.5	141.9

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