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Energy implications of mechanical and mechanical–biological treatment compared to direct waste-to-energy

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ABSTRACT

Primary energy savings potential is used to compare five residual municipal solid waste treatment systems, including configurations with mechanical (MT) and mechanical–biological (MBT) pre-treatment, which produce waste-derived fuels (RDF and SRF), biogas and/or recover additional materials for recycling, alongside a system based on conventional mass burn waste-to-energy and ash treatment. To examine the magnitude of potential savings we consider two energy efficiency levels (state-of-the-art and best available technology), the inclusion/exclusion of heat recovery (CHP vs. PP) and three different background end-use energy production systems (coal condensing electricity and natural gas heat, Nordic electricity mix and natural gas heat, and coal CHP energy quality allocation).

The systems achieved net primary energy savings in a range between 34 and 140 $MJ_{primary}/100\ MJ_{input\ waste}$, in the different scenario settings. The energy footprint of transportation needs, pre-treatment and reprocessing of recyclable materials was 3–9.5%, 1–18% and 1–8% respectively, relative to total energy savings. Mass combustion WtE achieved the highest savings in scenarios with CHP production, nonetheless, MBT-based systems had similarly high performance if SRF streams were co-combusted with coal. When RDF and SRF was only used in dedicated WtE plants, MBT-based systems totalled lower savings due to inherent system losses and additional energy costs. In scenarios without heat recovery, the biodrying MBS-based system achieved the highest savings, on the condition of SRF co-combustion. As a sensitivity scenario, alternative utilisation of SRF in cement kilns was modelled. It supported similar or higher net savings for all pre-treatment systems compared to mass combustion WtE, except when WtE CHP was possible in the first two background energy scenarios. Recovery of plastics for recycling before energy recovery increased net energy savings in most scenario variations, over those of full stream combustion. Sensitivity to assumptions regarding virgin plastic substitution was tested and was found to mostly favour plastic recovery.

1. Introduction

The well-established alternatives to treating mixed or residual municipal solid waste (MMSW) today are mass grate combustion or thermal Waste-to-Energy (WtE), different Mechanical–Biological Treatment (MBT) concepts followed by energy recovery and direct disposal through landfilling. Many less proven alternatives also exist, such as waste pyrolysis, gasification and mechanical heat treatment (e.g. Papageorgiou et al., 2009; Arena, 2012). The waste refinery concept is another alternative that has been materialised in Denmark through the Renescience technology (Tonini and Astrup, 2012).

A number of studies have been dedicated to comparing the energy efficiency and overall environmental performance of direct WtE and Mechanical–Biological Treatment configurations (e.g. Consonni et al., 2005a,b; Christensen et al., 2009; Papageorgiou et al., 2009; Koci and Trecakova, 2011; Ketelsen, 2012). Zeschmar-Lahl (2010) made a review of six studies performed in Germany between 2003 and 2009. Results vary widely between studies, depending on system boundaries, background conditions and assumed process efficiencies across treatment chains. In general, no consensus has been reached, as both alternative treatment strategies are found to be preferable in different conditions and regional settings.

For example, Consonni et al. (2005a,b) compared four generic scenarios based on waste management strategies implemented in different regions of Italy. The first strategy, in which residual waste is treated directly in a conventional WtE plant, is compared to strategies where the waste is subjected to a light mechanical treatment followed by waste incineration (strategy 2), mechanical biological

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stabilization – MBS (strategy 3) and classical composting MBT (strategy 4), both followed by refuse-derived fuel (RDF) utilisation in a fluidized bed combustor. Comprehensive mass and energy balances showed that additional energy use and specific losses during processing determined lower energy savings in all alternatives compared to direct WtE. In a subsequent study, Consonni et al. (2006) added co-combustion of RDF in coal-fired power plants and utilisation in cement kilns. Both alternatives showed similar or better energy savings compared to conventional WtE. These results were recently augmented by Rigamonti et al. (2012), supported by long term monitoring in a coal-fired power plant.

Wallmann et al. (2008) calculated the energy efficiency of different MBT concepts (MBT with composting, -with biogas and biological drying MBS) by making primary energy balances based on operational data from 18 to 20 plants. System boundaries started at plant and ended with the outputs generated. Electricity, gas and diesel used in plant operation were converted to primary energy by using coefficients that account for the cumulated energy demand of their production and supply. The calculation stopped at considering the energy content of energy carrying outputs (i.e. RDF and biogas) as primary energy further available. Results showed that, on average, 59–72% of the energy invested in the MBT systems was available in their outputs. Ketelsen (2012) developed a balancing model which calculates energy efficiency and climate-relevant CO_2 emissions for process combinations using MBT technologies. Input data from 15 facilities (MBT plants) was used to calculate the respective parameters and then make an overall comparison to direct thermal treatment of waste. Results reflected a great variability in energy efficiency and CO_2 footprint between MBT plants and their extended energy recovery systems. On average, however, MBT waste management systems had an advantage over direct thermal treatment.

Material recovery from municipal solid waste has been, on the one hand, addressed in many comprehensive studies which compare different source separation and collection methods (e.g. Dahlén et al., 2007; Larsen et al., 2010; Bernstad et al., 2011). Nevertheless, considerable amounts of recyclable materials are left in the residual stream even in waste management systems with extensive separate collection. On the other hand, studies which assess residual waste treatment strategies are usually focused on energy recovery alternatives and their efficiencies and are recurrently handling resource recovery in a generic and limited way. Van Berlo and De Waart (2008) compared variants of landfilling and variants of WtE by using an array of different performance indicators such as primary resources, diversion rate, energy efficiency, the R1-formula, exergy efficiency and CO_2 balance. Advantages and shortcomings of the different methods of evaluation are discussed together with the relevance of their results. The study concluded that performance indicators that combine conversion efficiency to energy products with resource efficiency (substitution of primary materials) and application efficiency (e.g. quality of energy) can offer a more comprehensive base for development strategies in waste management.

Mechanical and mechanical–biological treatment processes manipulate and convert raw waste into different streams which are directed either to material recycling, energy recovery or disposal. They create opportunities to recover additional resources and broaden the range of possible energy recovery applications, including high efficiency industrial processes. However, they also increase system complexity, they add inherent system losses and induce additional energy consumption. Considerable research has yet to be dedicated to demonstrate the environmental, resource and socio-economic relevance of these alternatives (Velis and Cooper, 2013). In the present study five residual waste treatment systems are compared from a holistic perspective by means of life cycle energy balances. The main objective was to contribute to the understanding of energy and resource efficiency of such complex integrated systems considered alternatives to conventional WtE. The magnitude of potential savings was examined considering different technological energy recovery alternatives, variation in energy recovery efficiency and the influence of different background conditions and end-use energy production.

2. Methodology

2.1. Life cycle energy balance

The comparison of alternative systems for residual waste treatment has been addressed in this study by performing a complete life cycle energy balance for each system. Each system consumes materials and energy in order to operate, accounted for as system burdens or *induced flows*. During the treatment process, recovered and utilised materials and energy are generated, and accounted for as functional outputs from the system. These functional outputs are modelled to include the markets at which they are sold and at which they replace alternative supplies of the same functional outputs. The scope of the modelled system is, then, expanded to include these replaced alternative flows, also called *avoided flows*. The waste treatment system is, thus, credited with substituting a similar amount of materials or energy produced from primary sources. Similar to full Life Cycle Assessment (LCA) studies, all induced and avoided flows are included from the initial induced fuel/ore extraction to the final avoided fuel/ore extraction, thus providing an account of all cumulated energy along the whole chain of operations. This energy accounting is also expressed as the *primary energy* balance. Hence, induced and avoided material streams are also converted and expressed as the energy value of all induced/avoided fuel and feedstock in their supply chain. The result of the life cycle energy balance is a net quantity of primary energy, expressed as $kg_{oil\ eq.}$ or $MJ_{primary}$ per unit processed waste, which in turn is the difference between total primary energy induced and total primary energy avoided by that system.

2.1.1. System boundaries

Upstream burdens for the production and use of the materials that end up in waste are not considered based on the "zero burden" assumption used in LCA of waste management systems (Ekvall et al., 2007). System boundaries are illustrated in Fig. 1. Alternative treatment systems start at the point of waste generation, with collection and transport of waste to the first system process, namely pre-treatment. Intermediary products generated during pre-treatment are sent to further refining, energy recovery or directly to disposal. Secondary wastes arise at this point (e.g. sorting residues, bottom ashes) which are reprocessed or directly disposed of. In the third step, material streams (i.e. metals and plastics) are reprocessed to secondary materials. Secondary produced materials and recovered energy replace primary materials produced from virgin sources and background energy production, on their respective markets. Secondary waste flows arising in final reprocessing were not included in the model.

For each unit process in the system, the primary energy equivalent of each process specific energy and material input is accounted for, and outputs are modelled by efficiency coefficients which determine intermediary to final outputs. Any transport/transfer from one unit process to another has been accounted for as energy (diesel) consumption by transportation.

The five alternative systems assessed in this study are described in detail in Section 2.2. The essential difference between alternatives is the pre-treatment step, while energy recovery and material reprocessing steps are defined in a set of common scenarios. Mass and energy flows within pre-treatment processes are based on

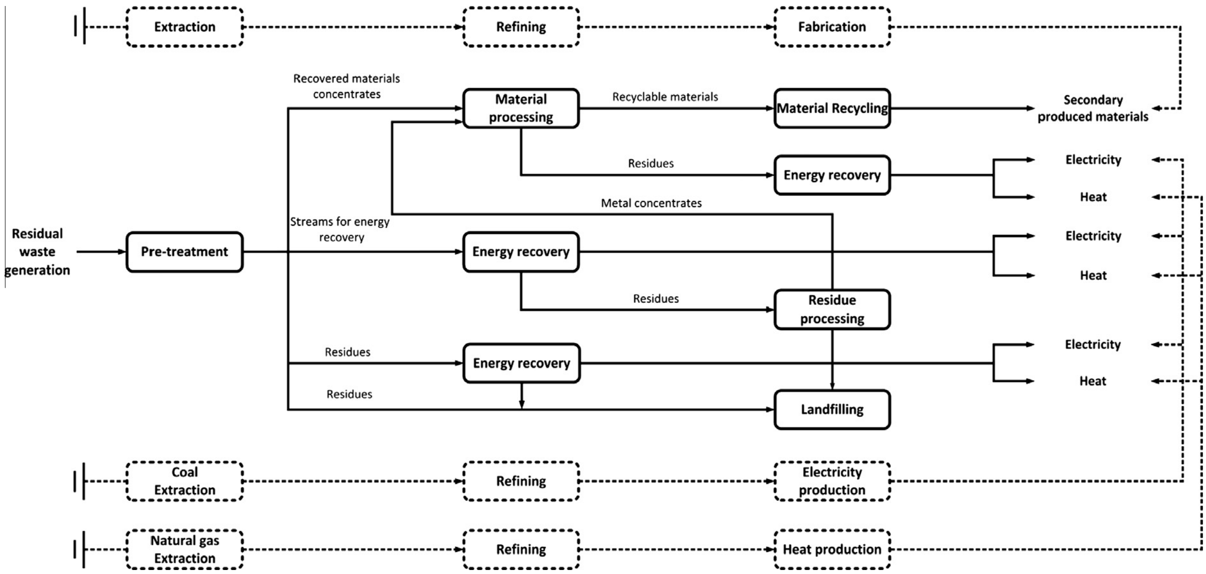

Fig. 1. Conceptual system model for residual waste treatment.

specific yearly operational data from three plants described in Section 2.2.1. Due to small differences between the plants, in the calorific value of the input waste processed, it was assessed that energy balances per tonne input are not directly comparable. A further normalisation of the primary energy balance results was applied, whereby consumption and savings were quantified relative to energy content of input waste. Results both before and after normalisation are presented in the results section of this paper.

2.1.2. Efficiency levels of compared technologies

Waste-to-energy plants in this investigation comprise of (1) conventional mass grate thermal treatment plants and (2) dedicated, so-called RDF mono-combustion plants. They have considerably different energy efficiencies across Europe depending on a variety of factors including the age and size of plants, location, which is crucial for possibilities to market energy outputs, and the existence of national incentive programmes which support optimisation and technological advances in energy recovery. This is shown by studies that have reviewed large numbers of waste incineration plants, such as that of Reimann (2009) and Grosso et al. (2010).

In this study both RDF and SRF (solid recovered fuels) denote combustible, high calorific value waste mixtures separated by mechanical treatment from residual waste, however, with the important distinction that SRF is prepared to meet certain quality requirements which make it suitable for advanced energy recovery applications such as co-combustion with conventional fossil fuels in industrial plants (Velis et al., 2010).

In order to reflect the wide range of variation found in energy efficiency of waste-to-energy plants across Europe, and to allow comparisons of alternatives on an equal footing, two main technological efficiency scenarios have been defined:

- SotA (State-of-the-Art): Energy recovery efficiency equals the average of new WtE plants constructed in Europe. RDF/SRF streams are modelled used in mono-combustion plants.
- BAT (Best Available Technology): Energy recovery efficiencies equal the best case WtE in operation today. SRF streams are co-combusted with coal in coal-fired power plants.

These main technology scenarios have two variations: (1) heat utilisation is possible and WtE includes *CHP production*, (2) heat utilisation is not possible and WtE includes only electricity or *PP production*. Technologies and selected efficiencies are described in detail in Section 2.2.2.

2.1.3. Background or primary energy production

The primary energy demand to produce end-use energy such as electricity and heat, differs to a large extent based on the conversion technology and source of primary energy used (e.g. coal, natural gas, renewable). As such, a comparison of waste treatment systems based on their potential for primary energy substitution is only feasible by choosing background energy systems and using them as the reference against which energy production from waste is assessed, i.e. type of energy production avoided by waste-recovered energy.

Three background energy production systems were chosen in this study. Conversion coefficients to primary energy were determined from Dones et al. (2007) and are presented in Table 1. These coefficients account for energy spent in extraction, refining, provision of fuels, supplementary fuel used for start-up operations and energy conversion in the energy production plants.

- Coal PP and natural gas – this background energy system scenario assumes electricity production in condensing coal-fired plants (average plant in Scandinavia, PP – power production only) and heat production in decentralized natural gas boilers.
- Nordel mix and natural gas – this background energy system scenario assumes electricity production based on the Nordic electricity mix in 2000 described in Dones et al. (2007), which combines the national mixes of Denmark, Norway, Sweden and Finland. Nordel accounts for a mix with shares of non-renewable sources, i.e. fossil and nuclear, and large shares of renewable sources such as biomass, hydropower, and wind-solar-geothermal. Heat production is still assumed from decentralized natural gas boilers.
- Coal CHP with allocation based on energy quality – this background energy system scenario assumes both heat and electricity is produced in large efficient CHP coal-fired power plants with an efficiency of 40% electricity and 45% heat (DEA and

Table 1
Primary energy conversion coefficients.

Energy product	Coal PP scenario ($MJ_{primary}$/ $MJ_{energy\ product}$)	Nordel 2000 mix scenario ($MJ_{primary}$/ $MJ_{energy\ product}$)	Coal CHP energy quality scenario ($MJ_{primary}$/$MJ_{energy\ product}$)
Electricity	3.18	2.26	2.43
Heat	1.40	1.40	0.28

Energinet, 2012). The primary energy (mainly the fuel used) for production of electricity and heat is allocated between the two outputs using the energy quality method described by Fruergaard et al. (2009), and are reflected in the coefficients for this scenario (Table 1).

Daily and seasonal variation in heat demand has been considered and therefore, as a baseline condition, only 70% of produced heat in all CHP scenarios substitutes heat produced in the background energy system.

2.1.4. Primary production of materials and fuels

The primary energy demand for virgin metals production was calculated based on data from Classen et al. (2009). The final figures used account 23 MJ kg^{-1} for virgin steel, 194 MJ kg^{-1} for virgin aluminium and 60 MJ kg^{-1} for virgin copper production. The primary energy demand for production of virgin plastic granulates was calculated based on Hischier (2007). The figure chosen, 80 MJ kg^{-1} plastic granulate, reflects the average of four types of virgin plastic, which are the most commonly used in packaging found in MSW (i.e. PET, HDPE, LDPE and PP). Primary fuels, such as hard coal, natural gas and diesel are consumed in the treatment processes and transportation or are avoided by secondary recovered products. The primary energy necessary for extraction, refining and provision of these fuels has been calculated based on the report by Dones et al. (2007).

2.2. Alternative residual waste treatment systems compared

The main difference between the alternative systems investigated lays in the type of pre-treatment applied and, therefore, the names chosen for the systems reflect the pre-treatment process.

- MBT Composting – mechanical biological treatment with composting of the organic fine fraction.
- MBT Anaerobic digestion – mechanical biological treatment with biogas production (dry AD).
- MBS Biological drying – mechanical biological stabilization or biodrying MBT.
- MT Mechanical pre-treatment – mechanical processing before energy recovery.
- WtE Mass combustion – conventional mass grate combustion without pre-treatment.

2.2.1. Mass and energy flows within pre-treatment

Mass flows were established based on yearly operational data in three plants described in the sections below. Available analytic data on inputs and outputs in the same plants was used to establish energy balances related to waste energy content. Process energy consumption figures are based on operation in the specific plants except for MBT Composting and MBT Anaerobic digestion which are averages of 7 and respectively 6 German plants (Ketelsen, 2012).

2.2.1.1. MBT Composting. The pre-treatment section within the treatment chain for this alternative is represented by mechanical and biological processing which takes place in an MBT plant based on the *material stream separation concept* (Thiel and Thomé-Kozmiensky, 2010). The Ennigerloh MBT plant in Germany, which was used to establish mass and energy balances, receives residual or mixed MSW from households (70%) and similar Commercial and Institutional waste (C&I – 30%). The waste from the two sources is processed on two lines which merge after initial size reduction and sieving. At this point, the waste has a LHV of 10.8 MJ kg^{-1}. A simplified process flow diagram with mass and energy balances is presented in Fig. 2a. The outputs from mechanical processing are (1) metal concentrates, (2) two middle calorific (RDF) fractions and one high calorific (SRF) fraction (LHV 19–23 MJ kg^{-1}), and (3) a fraction with low calorific value containing most of the biodegradable organic and inert material fractions. The SRF is further 'negatively sorted on NIR machines, i.e. to remove PVC plastics, and is size reduced to 20–30 mm in order to be sold as high quality alternative fuel. The low calorific organic fraction is composted and stabilized before being landfilled in special cells. The two RDF streams are sent to dedicated mono-combustion plants while the PVC rich residues are sent to conventional thermal treatment plants. The total end-use energy consumption for pre-treatment was modelled as electricity - 45 kW $h_{el.}$ and natural gas - 41 kW h_{NG} per tonne of processed waste.

2.2.1.2. MBT Anaerobic digestion. Pre-treatment was modelled in this alternative based on the same composting MBT plant with the important difference that the organic fine fraction is first used for biogas production and subsequently the digestion residues are stabilized before being landfilled. Anaerobic digestion is based on the study by Ketelsen et al. (2010) and consists of a single stage mesophilic, dry digestion process. Typical biogas yields in German plants are between 130 and 150 Nm^3 per tonne input to digestion with a CH_4 content of 55%. In this study, the organic fine fraction constitutes about 40% of the input to pre-treatment, which corresponds to a production of 57 Nm^3 biogas per tonne input waste (biogas LHV is 19 MJ/Nm^3). The total end-use energy consumption modelled consists of 65 kW $h_{el.}$ and 58 kW h_{NG} per tonne of processed waste.

2.2.1.3. MBS Biological drying. Mass and energy flows are based on the MBS plant located in Osnabrück, Germany, which is treating residual waste from households with a LHV of approximately 9 MJ kg^{-1}. Pre-treatment consists of coarse shredding before the biological drying process, followed by intensive mechanical processing (Fig. 2b). For a comprehensive review of process and engineering for bioconversion by biological drying please refer to Velis et al. (2009). Biological drying is performed in closed reactors and is optimised to preserve most of the calorific value of degradable organic matter by controlling the biodegradation process (duration of 7 days). In the mass balance established for this plant, incoming waste is reduced by approx. 28%, consisting of 25% moisture and 3% easily degradable dry matter. The dried waste is mechanically processed to recover metal concentrates and remove inert materials (e.g. stones, glass), which are landfilled. The remaining stream constitutes a high calorific SRF with a LHV of around 15 MJ kg^{-1}. Pre-treatment energy use amounts to 100 kW $h_{el.}$ and 25 kW h_{NG} $tonne^{-1}$.

2.2.1.4. MT Mechanical pre-treatment. Mass and energy flows as well as energy consumption for pre-treatment, in this alternative, is modelled based on operational experience in the large integrated waste management facility in Wijster, the Netherlands (described by Woelders et al. (2011)). Here, residual MSW from households (80%) and similar C&I waste (20%) with a LHV of 10.5 MJ kg^{-1}

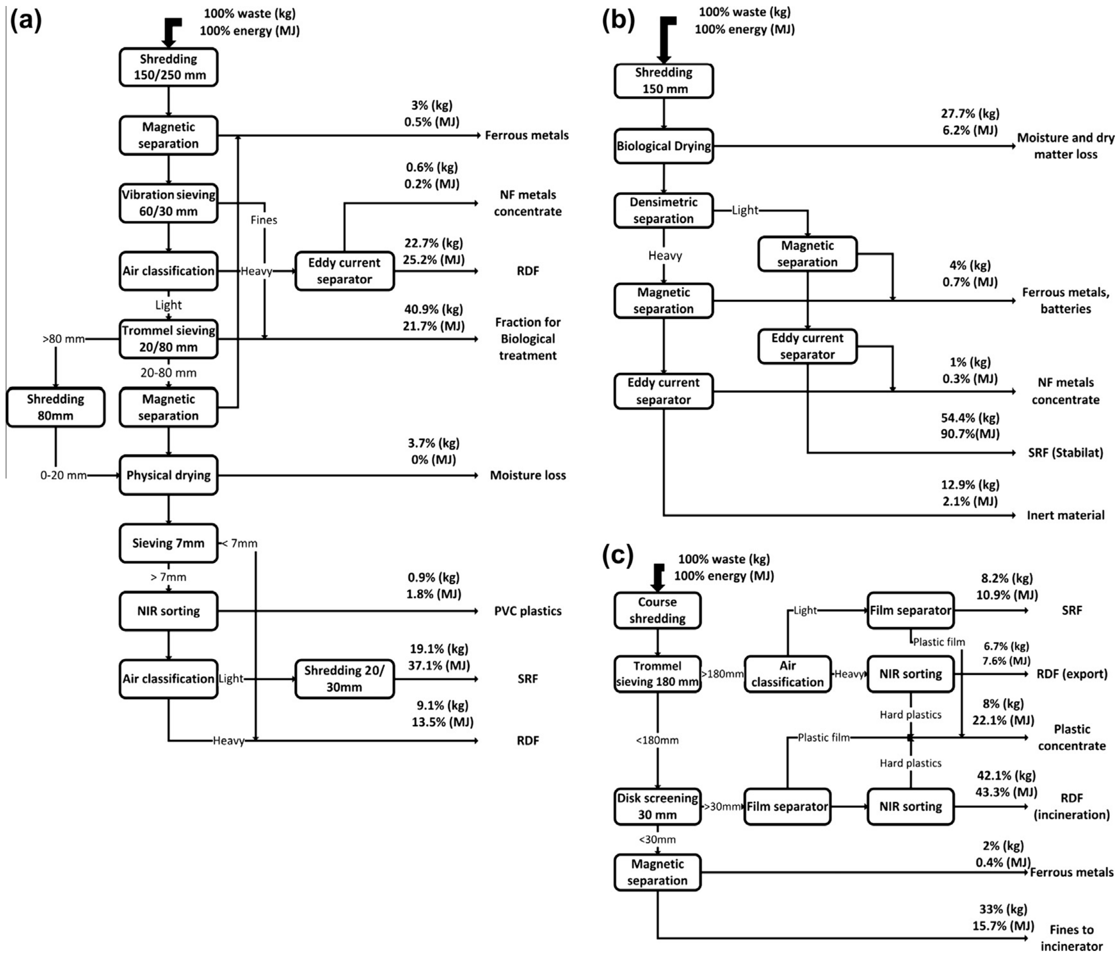

Fig. 2. Mass and energy flows in pre-treatment: (a) mechanical part of MBT Composting (b) MBS Biological drying and mechanical treatment (c) mechanical treatment (MT) before energy recovery.

was mechanically processed on three identical lines in order to remove high calorific fractions before the remaining stream was fed to the attached WtE plant without further treatment. By the end of 2010, one of the three lines was upgraded with additional unit processes (including NIR sorters) in order to remove plastic fractions for recycling from the treated waste. The efficiency of this line was documented by Van Velzen and Jansen (2011). The upgraded line is the basis for pre-treatment used in this study and a simplified process flow diagram is presented in Fig. 2c. The waste received by the plant comes from municipalities that do not have separate collection of plastic packaging waste. The so called "post separation" process for plastics performed "centrally" at the plant is recognised by the Dutch authorities as an alternative and complementary to source separation and separate collection. The plastic concentrates removed, consisting of hard plastics and a foil plastic concentrate, represent about 8% of the mass fed to this process line. However they also make up to around 20% of the energy content in the waste which is then, of course, unavailable for the subsequent energy recovery. Additionally, the process generates a high calorific SRF (14 MJ kg^{-1}) and a middle calorific RDF (12 MJ kg^{-1}) which are also exported for energy recovery. The remaining mixture, which is fed to conventional WtE, constitutes around 75% by weight of the initial input and has a LHV just above 8 MJ kg^{-1}. End-use energy consumption for mechanical processing is 15 kW $h_{el.}$ per tonne waste processed.

2.2.1.5. WtE Mass combustion. This alternative involves no pre-treatment of waste. The waste input was modelled as residual MSW with a LHV of 10 MJ kg^{-1}, constituting of domestic waste (80%) and similar C&I waste (20%). Bottom ash is processed to recover metals and is deposited in a landfill (further detailed in Section 2.2.3).

2.2.2. Energy recovery after pre-treatment

Typical new waste incineration plants in Europe, which can be considered state-of-the-art, have net electrical efficiencies between 18% and 24%, mainly depending on their size and boiler steam parameters (Van Berlo and De Waart, 2008). However, there are several examples of highly advanced WtE plants with significantly higher electrical efficiencies (Gohlke and Martin, 2007; Gohlke et al., 2007). These plants employ a range of measures to increase efficiency, such as increased steam parameters, reduced air rate and intermediate reheating, in order to achieve net waste-to-electricity efficiencies of up to 30–32%, exemplified by the WtE plant in Amsterdam. Further increases can be achieved for example by external superheating in fossil-fired boilers (e.g. WtE plants in Mainz and Bilbao), however these options were beyond the scope of this study.

In northern Europe, heat recovery plays an important role and, WtE plants are usually optimised for combined production of heat and electricity (CHP). CHP production implies a reduction in the amount of electricity that can be produced (i.e. electricity derating). The usual approach to calculating electricity derating is by using the Carnot factor for heat (Fruergaard et al., 2009; DEA and Energinet, 2012). However, this approach does not take into consideration that state-of-the-art CHP plants, compared to PP plants, are optimised for high recovery of residual heat, including flue gas condensation in many cases, which allows for both efficient electricity and heat recovery. In this study, electricity derating was accounted for by choosing appropriate efficiency levels consistent with state-of-the-art and best available examples of existing WtE plants.

RDF mono-combustion plants are essentially waste incineration plants built to accommodate feedstock with a high degree of variation in calorific value such as middle calorific RDF streams. RDF with a more homogeneous particle size distribution allows for the use of fluidized bed systems additionally to grate combustion systems (Friege and Fendel, 2011). However, energy recovery efficiency is only marginally improved by the use of RDF compared to raw residual waste, mainly due to limitations to boiler steam parameters, which apply for both types of fuel.

Approximately 800,000 tonnes of SRF were co-combusted in coal-fired power plants in 2010 in Germany, 78% of which in brown or lignite coal-fired and 22% in hard coal or black coal-fired power plants. A thorough and updated overview of the situation of co-combustion of SRF in coal-fired power plants in Germany can be found in Thiel and Thome-Kozmiensky (2012). Requirements on SRF quality are higher than for any alternative thermal recovery options (e.g. cement kilns, RDF mono-combustion) and the risk of severe technical damage by the use of SRF to modern high-efficiency Benson boilers (i.e. supercritical steam state boilers) restricts the use of SRF to older power plants (Friege and Fendel, 2011). Maier et al. (2011) reported the average electricity efficiency of nine coal-fired plants that co-combust SRF at 35–36%, which is lower than the state-of-the-art of 40–44% for pulverized coal-fired plants with advanced steam processes.

2.2.2.1. Efficiency of combustion-based techniques. WtE plants, both conventional and RDF combustors, were modelled with increasing efficiencies in the two main energy recovery scenarios, also for the scenario variations of CHP and PP. Efficiency parameters were settled in the SotA scenario to 18% net electricity and 60% heat recovery efficiency for CHP and 22% net electrical efficiency for power only, while in the BAT scenario, this was 26% net electricity and 60% heat recovery efficiency for CHP production and 30% net electrical efficiency for power only production respectively.

Pre-treatment techniques in the first four alternatives of the study produce SRF streams which were modelled co-combusted with coal in the BAT scenario. Due to the technical challenges of SRF co-combustion, it is assumed that the average coal-fired plant accepting SRF has lower electricity efficiency than the power plant modelled for the background power production. SRF was assumed co-combusted in a plant with 35% net electricity and 40% heat recovery efficiency in the case of CHP and a maximum 40% net electricity efficiency in the case of power only. Residues from plastic sorting and recycling were modelled utilised in cement kilns as alternative fuels, replacing coal on a 1 J:1 J basis.

2.2.2.2. Efficiency of biogas utilisation. Biogas is produced in one of the alternative treatment chains, MBT Anaerobic digestion. It was assumed that biogas is combusted in gas engines with generation of heat and electricity. Net electricity efficiencies for gas engines run between 40% and 48% and total efficiencies, with heat generation, between 88% and 96% (DEA and Energinet, 2012). A difference of 5% electricity efficiency was modelled between the two main energy recovery scenarios, with 40% net efficiency in the SotA and 45% in the BAT respectively. Heat recovery was maintained at a constant value of 40% of thermal energy input for both scenario variants allowing for heat utilisation.

2.2.3. Material recovery technologies

Metal concentrates, both ferrous and non-ferrous, are produced (1) in the mechanical processing steps of pre-treatment (first four alternatives) and (2) in the treatment process of bottom ashes in the MT and direct WtE alternatives. While in the first case the recovery of metal concentrates is part of the pre-treatment process in the system (accounting for energy consumption), bottom ash sorting is described separately for the second case. Ferrous and non-ferrous metal concentrates are assumed recovered in a specialised plant and they constitute 9% and 2% respectively of the weight of bottom ash processed (original data from a Danish plant). The energy consumption of 15 kW $h_{el.}$ per tonne bottom ash processed was modelled. Lastly, a plastic concentrate is generated in the MT alternative (described in Section 2.2.1.4).

Material concentrates recovered for recycling undergo a series of refining, sorting and final reprocessing steps before exiting the system as secondary materials that will substitute primary/virgin materials on the market. The final recycling efficiency (i.e. quantity of secondary produced materials) is affected by the individual efficiency of each processing step (Table 2).

2.2.3.1. Metal recovery and recycling. Analyses of metal concentrates generated in MBT plants and from bottom ashes after incineration show wide variations in actual metal content and metal type composition (e.g. Gillner et al., 2011; Gosten, 2012). In this study metals content has been conservatively generalised for all alternatives, to 70% in the case of ferrous metals and 50% for NF metals concentrates. At the same time, for the sake of simplicity, the metal composition is NF metals concentrates has been assumed to 70% aluminium and 30% copper.

Ferrous metals concentrates can be sent directly to steel producers if they comply with the requirements of these industries, however this is usually not the case (Damgaard et al., 2009). Ferrous metals concentrates separated in MBTs have high contents of impurities (non-metals), while concentrates from bottom ashes usually do not meet the maximum Cu content requirement. As such, ferrous concentrates might undergo an additional refining step within a metal scrap processing plant, such as a shredder facility, before being sent to a metal smelter. The latter has been assumed in this study and energy consumption of 100 $MJ_{el.}$ per tonne processed concentrate has been accounted. Non-ferrous concentrates have to be further refined to remove non-metal residues and undergo sorting into metal types. This process usually happens in specialised plants that employ heavy media separation. The energy consumption in these facilities is around 300 $MJ_{el.}$ per tonne processed concentrate (Wens et al., 2010).

Purified metal concentrates are traded on the world market and therefore production of secondary metals from scrap, at specialised metal smelters, was modelled based on generic data from Classen et al. (2009). The cumulated primary energy demand for ferrous metals reprocessing to steel was calculated to 9 MJ per kg and losses in the process were assumed at 10% of the scrap input. Aluminium and copper reprocessing take 24 MJ kg^{-1} and 28 MJ kg^{-1} primary energy respectively and process losses were assumed at 16% of input scrap. There are no quality differences between virgin or secondary produced metals and therefore a substitution ratio of 100% has been used.

2.2.3.2. Plastic recovery and recycling. The composition of plastic concentrates recovered in the pre-treatment plant (MT alternative) has been analysed by Van Velzen and Jansen (2011), with the plastic content being determined at 63%. The rest constituted materials sorted by error in the concentrate such as paper and cardboard. The concentrates are sent to plastic sorting plants where the main plastic types are separated (PET, PE, PP and plastic foil) and a plastic mix. Residues and unsorted plastics make up a high calorific SRF

Table 2
Efficiencies across the material recovery and recycling chain.

Materials	Material content in concentrates (wt%), (*A*)	Concentrate processing (wt%), (*B*)	Secondary materials production (wt%), (*C*)	Substitution of primary materials (wt%), (*D*)	Total chain efficiency (wt%), ($A*B*C*D$)
Ferrous metals	70/50[a]	95	90	100	60/43[a]
NF metals	50	95	84	100	40
Plastics	63	75[b]		80	38

[a] Ferrous concentrate recovered during pre-treatment in the MT alternative.
[b] This figure accounts for sorting, washing and re-granulation processes to produce final plastic recyclates.

(assumed LCV of 20 MJ kg^{-1} due to high shares of paper and cardboard) which is used as an alternative fuel in cement kilns. Energy consumption in the sorting plants is 160–220 $MJ_{el.}$ per tonne plastic concentrate (Bergsma et al., 2011). Subsequently, the separated hard plastics are processed into regranulate or flake recyclates. In the process, remaining contaminants are removed by series of operations including washing, drying and extrusion (also to remove odours). The hard plastic mix and plastic foil are usually treated as lower quality products and are processed to agglomerate which is a product mainly recycled/used into structural material applications (e.g. benches, roadside poles and sound barriers). Final reprocessing can occur at a different or at the same plant which first sorts the material (latter assumed in this study). A total loss of 25% of plastic materials was estimated for the entire chain (Table 2), which is also consistent with the findings of Rigamonti et al. (2009) and Bernstad et al. (2011). The energy consumption in final reprocessing step was estimated, based on Bergsma et al. (2011), to 4 $MJ_{el.}$ and 1.1 MJ_{NG} for each kg of plastic material processed.

Secondary plastics usually exhibit lower qualities than virgin plastics, and therefore it cannot be assumed that they substitute virgin plastics on a 1:1 basis. Hence, a substitution ratio of 80% has been set, based on a similar thinking as presented by Rigamonti et al. (2009).

2.2.4. Collection and transport

Energy consumption for waste collection and transport from households to the first pre-treatment facility has been accounted based on findings by Larsen et al. (2009). An average value of 5 L_{diesel} per tonne collected waste and 0.15 L_{diesel} $tonne^{-1}$ km^{-1} for a distance of 20 km transport has been used in the model. Transportation between treatment stages was modelled as long-haul truck with a diesel consumption of 0.03 L $tonne^{-1}$ km^{-1}. It was assumed that metal concentrates, RDF/SRF streams and bottom ash to landfill are transported for a distance of 100 km, while sorted metals and plastic concentrates to final reprocessing plants are transported for a distance of 500 km.

2.3. Sensitivity analysis

Some key assumptions made in baseline scenarios were tested. In the BAT scenarios, generated SRF streams were assumed to be co-combusted in coal-fired power plants. It is reasonable to say that this utilisation option is limited today, and will be further limited in the future, in newly constructed high efficiency plants, and due to decommissioning and long term phase-out of coal-based energy. The sensitivity of alternative systems to this energy recovery option was assessed by alternatively modelling the use of SRF streams in RDF dedicated mono-combustion plants and industrial cement production. A simple 1 J_{SRF}:1J_{coal} substitution rate was used in cement kilns. Another important assumption is with regards to recycling of plastics fractions and possibilities to replace virgin plastics (in the MT alternative). Different substitution ratios were tested and the effects on this system were assessed and discussed. In a different analysis, it was additionally modelled that residues from plastic sorting and reprocessing are sent to WtE plants instead of cement kilns.

3. Results and discussion

The results of the primary energy balance for each alternative, expressed in $GJ_{primary}$ per tonne input waste, are presented in Table 3, while the final normalised results, which illustrate primary energy savings per unit energy in waste input to systems are shown in Fig. 3. The aim of the normalised result presentation is to eliminate the differences in calorific value of the input waste flows in order to allow consistent comparison of alternatives. For illustrative reasons the result figures (Fig. 3) are presented per 100 MJ waste input to the systems, and are broken down to illustrate the individual contribution of processes or products. Positive values represent induced flows (primary energy consumption), while negative values show avoided flows (primary energy savings) due to substitution of virgin materials and energy in the background systems.

3.1. Overall results

As a general acknowledgment, it was observed that all alternatives achieve large primary energy savings, and that these savings are several times higher than total primary energy consumed to operate the systems. The magnitude of achieved savings is very different in the three background energy systems. The highest net energy savings are gained in the Coal PP background with heat recovery, which was expected due to the high primary energy cost of background end-use energy. The importance of heat recovery is evident, as significantly lower primary energy substitution is achieved in scenarios without heat recovery.

Transportation needs have a small energy footprint in all scenarios. Relative to total savings, 3–4.5% primary energy is spent for transportation in the Coal PP background with heat recovery, while this increases to a maximum of 5–9.5% in the Nordel mix background without heat recovery. The energy use in pre-treatment plants is a more significant burden to the systems. In this study, pre-treatment by MBS is more energy intensive than the other MBTs and is the main expenditure in this system, between 9% and 18% relative to total savings. The lowest total process energy consumption was observed for WtE Mass combustion and this is attributed almost entirely to transportation needs.

3.2. State-of-the-Art (SotA) efficiency scenario

In this technological efficiency scenario two treatment alternatives stand out by having consistently better performances in all three background energy systems, namely WtE Mass combustion and MT Mechanical pre-treatment. In background conditions with electricity production only, and in the Coal CHP background, the MT alternative actually outpaced WtE considerably, displaying 15–30% more primary energy savings. This is due to the savings brought by material recovery (mainly plastics recycling) which remain constant in the different backgrounds, thereby making this system less vulnerable to changes in background energy systems.

All MBT-based systems showed between 14% and 29% lower primary energy savings compared to WtE Mass combustion. This is explained by additional energy consumption and losses in waste energy content during pre-treatment. Co-combustion of SRF streams was not included in the SotA scenarios (Section 2.1.2), specifically to show the effects when overall efficiency is constrained by RDF/SRF utilisation in conversion techniques with efficiencies similar to conventional WtE. These results for the SotA scenario are in agreement with findings by Consonni et al. (2005a,b), which were obtained by using similar system settings with regard to energy recovery. MBT Anaerobic digestion and MBS Biological drying perform similarly in the SotA scenario, as increased recovery of electricity and heat in the MBS alternative is upset by the slightly larger energy consumption during pre-treatment.

3.3. Best Available Technology (BAT) efficiency scenario

For all alternatives, there is a significant increase in potential primary energy savings if the best available technology is used compared to standard or state-of-the-art. In scenarios allowing for heat recovery, BAT energy recovery determined an average increase in primary energy savings of 19% in the Coal background and 15% in the Nordel mix compared to SotA. On the other hand, if heat utilisation is not possible, an average increase of more than 30% was observed when using BAT instead of SotA. If both avoided heat and electricity are produced by large Coal CHP plants, the average difference between the SotA and BAT scenario was around 28%. This indicates that under these background conditions, maximising electricity recovery should be a priority.

Results under the BAT technology scenario show a closer ranking distribution, as several alternative treatment systems had similar net primary energy savings. Under background conditions permitting heat recovery, the WtE and the MT systems again achieved the highest net savings, but MBS and MBT Anaerobic digestion came very close, boosted by the high efficiency of SRF co-combustion.

If heat utilisation is not possible, again MT indicates possible gains brought by material recovery over other systems. Increased electricity recovery due to SRF co-combustion conditioned MBS Biological drying to achieve the highest savings in the Coal PP background and second highest in the Nordel mix. Without heat recovery, WtE Mass combustion was not able to deliver the same high net primary energy savings. SRF co-combustion improves the energy profile of MBT Composting, however it does not fully compensate for the energy content losses during pre-treatment. Production of electricity and heat from recovered biogas more than compensates for increased energy costs in MBT Anaerobic digestion, which had almost the same performance as WtE Mass combustion. These results have to be understood in light of the system and scenario settings modelled, however, they denote quite well, in the case of BAT, an almost ideal maximum efficiency case and its implications for energy savings.

3.4. Material recovery

Primary energy savings by substitution of virgin materials accounted for a significant share of total savings in all alternatives. Metals recovery contributed with between 5% and 22% of total primary energy savings in the SotA scenario, and between 4% and 13% of primary energy savings in the BAT scenario. Plastics recycling contributed to savings of up to 30% of total savings (in the combination scenario SotA-Nordel mix-no heat recovery), and down to 16% of total savings (in the combination scenario BAT-Coal-with heat recovery). In the MT scenario, material recovery (i.e. metals and plastics) and avoided coal accounted for as much as 49% of total primary energy savings (in the combination scenario SotA-Nordel mix-no heat). In scenarios where heat recovery was not possible material recovery became very important. This is further accentuated if the background electricity production has a relatively low primary energy demand (i.e. Nordel mix and Coal CHP).

3.5. Sensitivity analysis

With the given assumptions in the baseline scenarios, the performance of three systems is very similar: WtE Mass combustion, MT Mechanical pre-treatment and MBS Biological drying. However, primary energy savings in the MT and MBS systems are dependent on assumptions which are somewhat more uncertain that those of assumptions for direct WtE. The assumptions in question are (1) SRF co-combustion in coal-fired power plants and (2) possibilities regarding plastic recycling.

(1) First, in the BAT scenario, SRF streams were alternatively directed to dedicated RDF mono-combustion plants (sensitivity scenario BAT no co-combustion/CC). The most noticeable effect was in the case of MBS. Without SRF co-combustion there is a sharp drop in electricity recovery which, however, is partially compensated by an increase in heat recovery in respective CHP scenarios (example in Fig. 4 Sensitivity – coal PP background with heat recovery). As only relatively small streams are co-combusted in the other alternatives, the difference between the baseline BAT scenario and BAT no CC scenario are also smaller. Second, SRF streams were directed to industrial cement kilns both in the BAT and SotA scenarios (sensitivity scenarios SotA CK and BAT CK). Consequently, systems producing SRF streams performed slightly worse in both the Coal and Nordel mix backgrounds when CHP was possible. However, if heat recovery is not possible, or only to a low extent, and also in a Coal CHP background, the alternative use of SRF streams in cement kilns improved the performance of the same alternatives compared to baseline scenarios (Fig. 4 Sensitivity – Coal CHP example). In fact, it can be observed that, every alternative performs, in this case, better than direct WtE, in both the SotA and the BAT scenarios. With SRF utilisation in cement kilns, the ash content can be incorporated into the clinker product and thus substitutes for other mineral raw materials, such as limestone, sands and partly iron ore (Thomanetz, 2012). The energy savings from this additional material substitution have not been added in the calculation model, nevertheless, they are expected to have a marginal contribution. Similarly, bottom ash in all alternatives has been modelled including transportation to landfills, however, it would be in many cases used as subbase layer in road construction.

(2) Lowering the virgin plastic substitution ratio from 80% to 50% conditioned a performance decrease for the MT alternative, this however, did not change its ranking among the best performing systems. This suggests that even when a relatively small part of recovered plastics avoid virgin polymers, there are substantial benefits. The use of non-recycled plastic sorting residues has to be also carefully accounted. Changing the use of plastic residues from cement kilns to WtE had a minor effect on the energy balance. Substitution of other materials, such as wood lumber or concrete, instead of virgin plastics, has not been assessed in the present study. Astrup et al. (2009) show that, in this case, recycling could present no environmental benefit, however, if the alternative use of wood is to produce electricity, considerable gains can be achieved by induced energy savings.

4. Limitations and perspectives

The current study demonstrates a number of system dependencies and energy implications for residual waste treatment strate-

Table 3
Primary energy savings due to substitution in $GJ_{primary\ energy}/tonne_{waste\ input}$.

Efficiency scenario	Energy background	MBT Composting		MBT Anaerobic digestion		MBS Biological drying		MT Mechanical pre-treatment		WtE Mass combustion	
		With heat	No heat	With heat	No heat	With heat	No heat	With heat	No heat	With heat	No heat
SotA	Coal PP	9.1	5.2	10.6	6.3	8.6	4.8	12.0	8.3	11.5	6.9
	Nordel mix	7.9	3.7	9.1	4.5	7.5	3.5	10.8	6.7	9.8	4.9
	Coal CHP	4.6		5.5		4.3		7.6		5.9	
BAT	Coal PP	11.6	8.7	13.3	9.9	11.4	9.5	14.2	10.7	14.0	9.4
	Nordel mix	9.4	6.1	10.7	7.0	9.1	6.8	12.2	8.4	11.6	6.7
	Coal CHP	6.8		7.9		7.2		9.3		7.9	

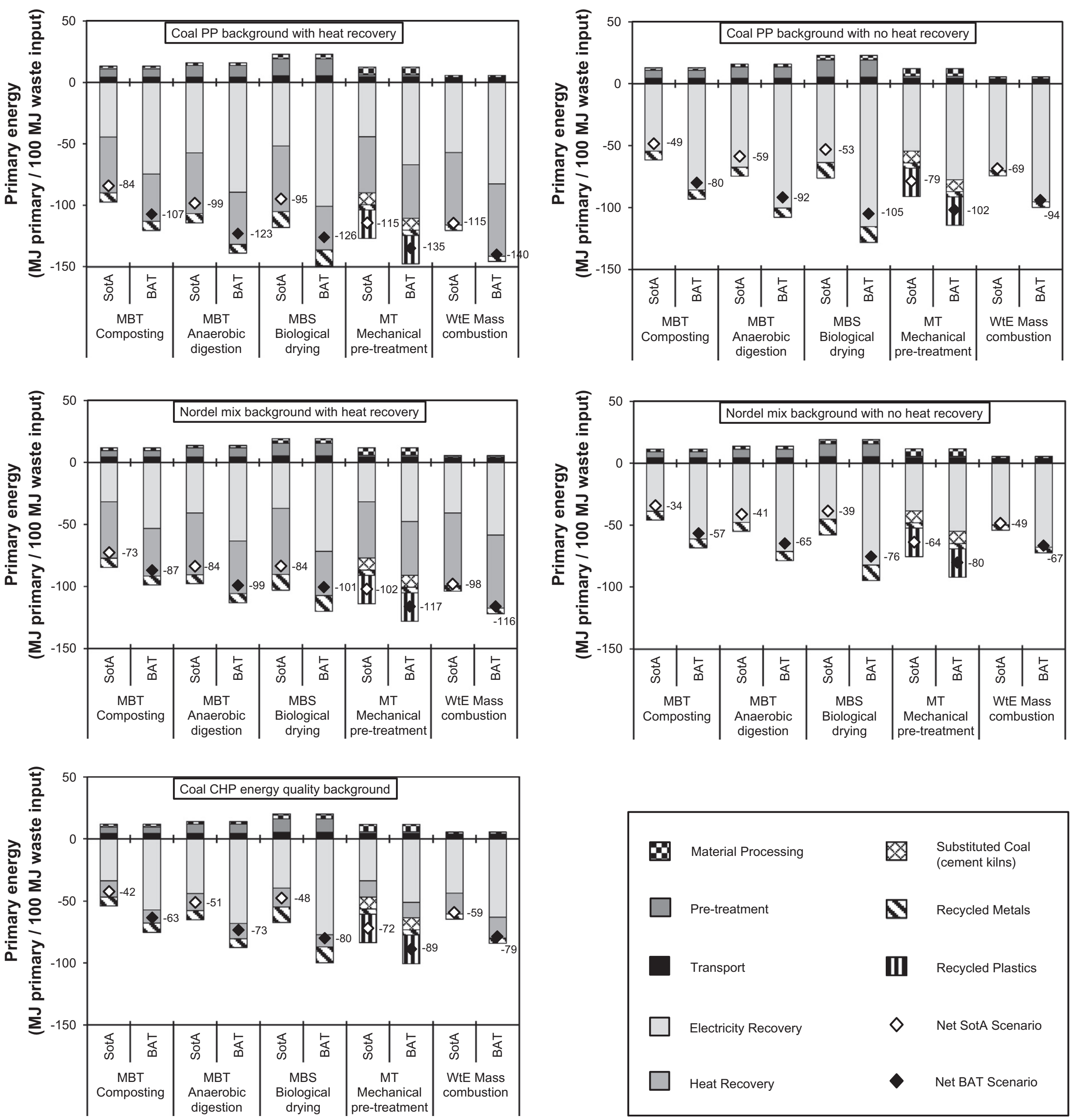

Fig. 3. Primary energy savings potential – Main results.

gies which use mechanical or mechanical–biological treatment for materials and before energy recovery, compared with direct thermal treatment. The chosen performance indicator, i.e. primary energy balance, is robust to variations and uncertainties of underlying energy and material production systems, however, it is also limited as it of course does not directly reflect environmental or socio-economic impacts and other consequences of implementing these different strategies.

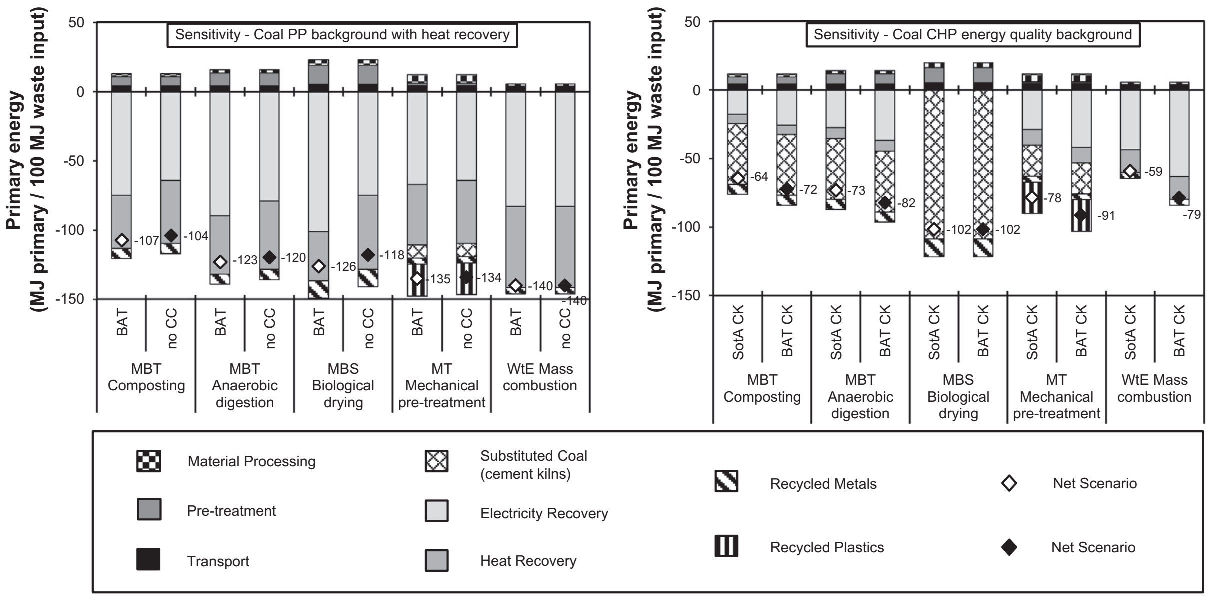

Fig. 4. Sensitivity analysis – (left side) BAT without the possibility of co-combustion (BAT no CC) in the Coal PP background scenario with heat recovery and (right side) SRF utilisation in cement kilns in the Coal CHP background.

Data from specific plants was used for the modelling of pre-treatment section in compared systems. Although chosen plants were intended to be representative for the different processing concepts, there are some limitations in the extent to which the results can be generalised. Except for the composting MBT, waste energy content losses in the other MBT pre-treatment plants were not large enough to overbalance the gains in energy efficiency by use of more advanced energy recovery routes. For the MBTs based on the material stream separation concept, biogas production from the organic fine fractions was paramount for high energy efficiency. In this sense, it is essential for MT and MBT systems, additional to any material recovery, to manage successfully energy flows, i.e. concentrate and direct most of the energy in waste towards a form of energy recovery, if an overall high efficiency is to be achieved compared to efficient mass combustion WtE. As an example, energy content losses in the MBT Composting system, modelled here, amounted to around 23% of input (Fig. 2). With SRF co-combustion, this system could not compete with conventional WtE on an equal footing in the BAT scenario. Yet, SRF use in cement kilns, when WtE CHP is not possible, did condition almost similar energy savings for the two systems. The results in the present study can be used as a clear indicator that production of high quality SRF alone, with high losses of energy content (in material streams disposed), can be insufficient to compete with conventional combustion of the entire unprocessed residual waste stream. A clear threshold for an acceptable level of losses is difficult to pinpoint, and would be different depending on background conditions (CHP vs. PP) and type of avoided energy production.

Potential primary energy savings by avoiding virgin material and energy production are relative to the type of assumed energy avoided. From a geographical scope, however, the three chosen background systems cover only to a very limited extent the complexity of energy systems in Europe. From a temporal scope, assuming that energy recovery from waste substitutes energy production from fossil sources is still valid in present conditions albeit not always. Renewable sources are playing an increasing role in the energy supply. In the future, large shares of energy generated from fluctuating renewable sources like wind and solar will additionally stress the balance between supply and demand, which will most likely favour energy technologies with increased production flexibility, including for energy recovery from waste.

Residual municipal waste is hardly storable due to the high content of biodegradable materials and high moisture content, which reduce its potential for flexible use as a fuel. It is additionally characterised by variations in composition, particle size distribution and can contain hazardous and problematic substances. Mechanical separation and sorting and mechanical–biological pre-treatment can be used to select, concentrate and prepare waste fractions for diversion towards more advanced material utilisation. From an energy utilisation perspective, waste-derived fuels and biogas are partially and, respectively, fully storable energy carriers. Future research efforts will include comprehensive environmental assessment of the role and consequences of sorting and separation systems for waste in the context of more concrete background conditions, including future renewable energy systems.

5. Conclusions

In this evaluation, the optimal conditions for residual waste treatment systems based on conventional thermal WtE were determined largely by opportunities for CHP production, which leads to high overall utilisation rates of the energy content in waste. The success of the three MBT based systems was indeed dependent on the efficiency of energy recovery routes after pre-treatment. A reduction in the amount of possible primary energy savings compared to mass combustion WtE is unavoidable, due to additional energy consumption and process losses, if RDF/SRF is only used in dedicated WtE plants.

When SRF streams were used in coal-fired plants, the energy balance of these systems improved substantially. MBT with anaerobic digestion and biological drying MBS systems achieved relatively similar primary energy savings as efficient CHP mass combustion WtE. In scenarios where CHP production was not possible, as is for example in southern European nations, the biological drying MBS system modelled achieved the highest savings of all systems, with full stream SRF co-combustion. With heat recovery not possible, but also if recovered heat was substituting heat from coal CHP, SRF utilisation in cement kilns (substituting coal) determined similar (composting MBT) and higher overall energy savings (MBT with anaerobic digestion and biodrying MBS) in systems with pre-treatment as opposed to conventional WtE.

Plastic recovery for recycling, by mechanical pre-treatment before energy recovery, supported similar or increased energy savings, in the different scenarios modelled, compared to full stream mass combustion. Sensitivity assessment showed overall system efficiency to be robust to different virgin plastic substitution ratios.

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