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Mass, energy and material balances of SRF production process. Part 3: Solid recovered fuel produced from municipal solid waste

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Abstract

This is the third and final part of the three-part article written to describe the mass, energy and material balances of the solid recovered fuel production process produced from various types of waste streams through mechanical treatment. This article focused the production of solid recovered fuel from municipal solid waste. The stream of municipal solid waste used here as an input waste material to produce solid recovered fuel is energy waste collected from households of municipality. This article presents the mass, energy and material balances of the solid recovered fuel production process. These balances are based on the proximate as well as the ultimate analysis and the composition determination of various streams of material produced in a solid recovered fuel production plant. All the process streams are sampled and treated according to CEN standard methods for solid recovered fuel. The results of the mass balance of the solid recovered fuel production process showed that 72% of the input waste material was recovered in the form of solid recovered fuel; 2.6% as ferrous metal, 0.4% as non-ferrous metal, 11% was sorted as rejects material, 12% as fine faction and 2% as heavy fraction. The energy balance of the solid recovered fuel production process showed that 86% of the total input energy content of input waste material was recovered in the form of solid recovered fuel. The remaining percentage (14%) of the input energy was split into the streams of reject material, fine fraction and heavy fraction. The material balances of this process showed that mass fraction of paper and cardboard, plastic (soft) and wood recovered in the solid recovered fuel stream was 88%, 85% and 90%, respectively, of their input mass. A high mass fraction of rubber material, plastic (PVC-plastic) and inert (stone/rock and glass particles) was found in the reject material stream.

Keywords

Solid recovered fuel, municipal solid waste, energy waste, mechanical treatment, material balances

Introduction

Management of municipal solid waste (MSW) is a vital issue in modern societies, as even the well planned and managed landfills may become problematic as far as the environment and public acceptance are concerned (Pinto et al., 2014). The European Commission requires reduction in landfilling to prevent or reduce, as far as possible, negative effects on the environment, in particular the pollution of surface water, groundwater, soil and air, and on the global environment, including greenhouse effect (Council Directive 1999). With the recovery of useful material and energy, MSW can be turned into an asset and resource.

In order to achieve the goals set for the waste utilisation, the recovery of energy from MSW is necessary (Luoranen and Horttanainen, 2007). A significant fraction of MSW consists of material (such as paper and cardboard, plastic, textile) that has high heating values. All the waste material produced in the society cannot be used for material recycling and moreover, the material recycling chains generate high amounts of residues, in some cases having high heating values (Garg et al., 2009; Umberto and Fabrizio, 2014). In order to recover energy from waste, the non-hazardous fraction of MSW can be turned into solid recovered fuel (SRF) to be utilised for energy recovery in incineration/co-incineration plants, and meeting the classification and specification requirements as per CEN standards (EN 15359). In this regard, the waste management sector industry over the years has developed ways to produce secondary fuels, such as SRFs.

In the European Union (EU), with the introduction of several technical documents, the classification of derived fuels from MSW has changed in recent years. These documents provide all the characteristics, definitions, sampling methods, parameters of

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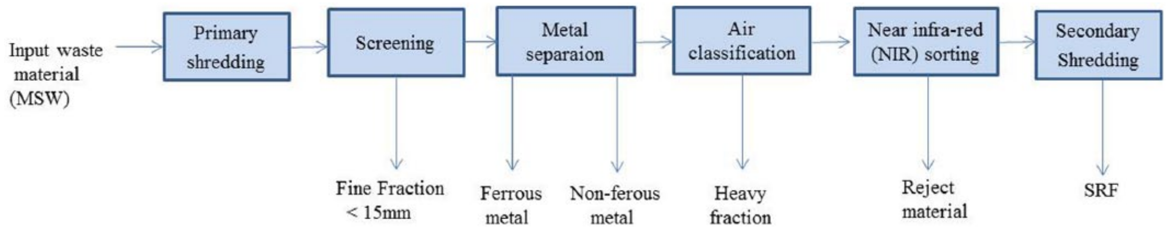

Figure 1. Simplified MT process to produce SRF from MSW.
MSW: municipal solid waste; SRF: solid recovered fuel.

interest and analytical methods for SRF (Rada and Andretottola, 2012). In Europe, SRF is used as a fuel/co-fuel in the cement industry and in the dedicated combustion and gasification plants. In Europe, SRFs are used successfully in terms of economic and environmental aspects (EN 15508). Use of SRF can reduce the cost of fuel and also the environmental impact in terms of CO_2 emissions.

In Europe, SRF is mainly produced through mechanical treatment (MT) or mechanical biological treatment (MBT) (Rada and Ragazzi, 2014; Ragazzi and Rada, 2012) methods. In order to produce SRF, the input waste material stream passes through a series of unit operations (such as shredder, screen, magnetic and eddy current separator, air classifier, optic sorting units and near- infrared (NIR) sorting unit, etc.) to sort out the impurities into separate small streams to produce a high yield of quality controlled SRF stream. At the moment in Finland, fraction of MSW that is complicated and economically not feasible to sort out for recycling purposes is treated in MT plants to produce SRF. SRF produced is used as a fuel/co-fuel in the cement industry and dedicated combined heat and power (CHP) gasification and combustion plants for energy recovery.

Studies are published that characterise the streams of material produced in the refuse-derived fuel (RDF) production process and describe them in the form of material balance (Rotter et al., 2004). There are a number of studies published that describe the characteristics of SRF in terms of its composition and proximate and ultimate analysis (Dunnu et al., 2010a, 2010b; Montané et al., 2013; Velis et al., 2011, 2013). But published studies are not found that evaluate the characteristics of various streams of material produced specifically in the SRF production process and present them in the form of material balance. In this research work, proximate and ultimate analysis of all the process streams (input and output) produced in the SRF production process is performed and their composition is determined. The SRF is produced from energy waste collected from households. Based on these analysis of process streams, their mass, energy and material balances for the SRF production process are established. All the process streams (input and output) produced in the SRF production plant were sampled and treated according to CEN standard methods for SRF.

This is the third and final part of a three-part article written to describe the mass, energy and material balances of the SRF production process. In order to state the context of this article (i.e. Part 3) with the other two parts (i.e. Part 1 and Part 2) the results of the balances presented in these articles are compared and discussed. Based on the results obtained from mass, energy and material balances of the SRF production process produced from three different types of waste streams, the most critical waste components are identified that affect the mass and energy balances of the SRF production process (see 'Comparison of results among three parts of study'). The mass, energy and material balances are presented in the form of Sankey diagrams. Sankey diagrams are designed to visualise the material flow balances in which the width of arrow is proportional to the quantity of flow.

Materials and methods

A commercial-scale experimental campaign was conducted to produce SRF from MSW (i.e. energy waste collected from households). In this regard, a batch of 30 tonnes of MSW was collected from the metropolitan area of Helsinki region and transported to a MT waste sorting plant to produce SRF. In this MT plant, the input waste stream was divided into various output streams of material: SRF, ferrous metal, non-ferrous metal, reject material, fine fraction and heavy fraction, as shown in Figure 1. The sorting of input waste stream into various output streams was based on particle size distribution, weight/density, ferrous/non-ferrous metal and NIR/specific spectral properties of waste components.

In the NIR sorting unit, components of waste material were classified based on their specific spectral/NIR properties. In this process there were two streams of reject material, i.e. reject (D_{95} 85 mm) and reject (D_{95} 120 mm) separated based on their particle size distribution. Detail of the process description is published elsewhere (Nasrullah et al., 2014a).

Sampling of process streams from SRF production plant

Sampling of process streams (input and output) from SRF production plant was performed according to CEN standard methods for SRF (EN 15442). Three different sampling methods were used to sample process streams from SRF production plant:

- sampling from a static lot;
- manual sampling from the static conveyor belt;
- manual sampling from the drop flow.

Use of different methods for the sampling of process streams was based on the operational condition and practical situation of SRF production plant. Streams of SRF, fine fraction, heavy

Table 1. Sampling of process streams from SRF production plant.

Process stream	Nominal top size D_{95} (mm)	Increment size[a] (kg)	Combined sample[b] (kg)
MSW (input material)	150	20	480
SRF	75	2.5	60
Reject (D_{95} 85 mm)	85	5.0	120
Reject (D_{95} 120 mm)	120	10	240
Fine fraction	10	1.0	24
Heavy fraction	150	20	80
Fe material	150	20	80
NFe material	150	20	80

[a]Increment size is the portion of material extracted in a single operation of sampling.
[b]Combined sample is the sum of 24 increments for MSW, SRF, reject (D_{95} 85 mm), reject (D_{95} 120 mm) and fine fraction streams, and the sum of four increments for heavy fraction, ferrous metal and non-ferrous metal.
SRF: solid recovered fuel; MSW: municipal solid waste.

fraction, ferrous metal and non-ferrous metal were sampled from a static lot. The input waste material stream (i.e. MSW) was sampled manually after primary shredding from the static conveyor belt and streams of reject material, i.e. reject (D_{95} 85 mm) and reject (D_{95} 120 mm), were sampled manually from the drop flow. Increment sizes of process streams were based on their respective nominal top size (D_{95}) and bulk densities, and 24 increments of each stream (except ferrous metal, non-ferrous metal and heavy fraction) were taken. Streams of ferrous metal, non-ferrous metal and heavy fraction were comparatively homogeneous in terms of their composition (see 'Composition of process streams') and, therefore it was not realised to take more than four increments of each of these three streams. Increments of each stream were combined together to form their respective combined samples. Sampling quantities of process streams taken from SRF production plant, their nominal top size, increment size and combined samples are given in Table 1.

Sample preparation of process streams for laboratory analysis

In order to sustain the representativeness of samples of process streams, the further sample preparation for laboratory analysis was performed according to CEN standard method for SRF (EN 15443). Sample preparation of process streams for laboratory analysis was done at two stages: outside the laboratory (before sending samples to the laboratory) and in the laboratory (after sending samples to the laboratory). Each stage for each sample preparation of process streams included:

- particle size reduction;
- sample division (mass reduction).

Equipment used to reduce particle size of samples was: shredder, screens of various mesh sizes, cutting mill, crushing mill and grinding mill. Methods used for sample division (mass reduction) were:

- manual increment division;
- riffle divider.

After sample preparation of process streams, their nominal top size (D_{95}) and mass size were reduced to 0.5–1 mm and 0.5–5 g. respectively, for final laboratory analysis. Samples of reject (D_{95} 85 mm) and reject (D_{95} 120 mm) were combined together into one stream sample as reject material for its laboratory analysis.

A detailed process description, as well as the sampling method used in SRF production plant and the sample preparation for laboratory analysis, is described in Part 1 of this work (Nasrullah et al., 2014a).

Results and discussion

Samples of process streams were analysed in the laboratory for various parameters, such as moisture content, ash content, volatile matter, biomass content, heating value and CHONS (carbon, hydrogen, oxygen, nitrogen, sulphur) content. Standard methods used for laboratory analysis of process streams are given (Nasrullah et al., 2014b).

The net calorific value (NCV, dry) of the SRF produced from MSW was measured in the laboratory as 22.4 MJ kg^{-1}. High calorific value of the SRF stream was owing to the strong contribution of paper and cardboard and plastics in it. Net calorific values (NCV, dry) of plastic (soft), plastic (hard) and paper and cardboard are reported as 37.0 MJ kg^{-1}, 35.0 MJ kg^{-1} and 16.0 MJ kg^{-1}, respectively (Nasrullah et al., 2014a). Plastics are the main components that lead to higher calorific values in the fuel (Rotter et al., 2004). Heating value (i.e. lower heating value (LHV) 23.56 MJ kg^{-1}, dry) of SRF is reported in literature (Vainikka et al., 2011). Biomass content of this SRF was measured in the laboratory as 50.8% C (bio carbon). Biomass content of SRF produced from construction and demolition waste (C&D waste) is reported as 66.7% C (bio carbon) (Nasrullah et al., 2014b). Biogenic components of SRF are reported in the range of 40%–80% (Hansen et al., 1998). High ash content in heavy

Table 2. Laboratory analysis results of process streams produced in SRF production plant produced from MSW (energy waste collected from households).

Streams	Moist. cont. wt%	Ash 550 °C wt%	Volat. matter wt%	Bio[a] cont. %C	C (d.) wt%	H (d.) wt%	N (d.) wt%	S (d.) wt%	$O_{calc.}$ (d.) wt%	NCV (a.r.) MJ kg^{-1}	NCV (d.) MJ kg^{-1}
MSW[b]	13.5	22.4	n.a.	n.a.	47.0	6.2	0.5	0.2	19.6	16.7	19.6
SRF	15.0	9.8	79.4	50.8	53.0	7.4	0.6	0.2	28.0	20.2	22.4
Reject	26.8	32.5	n.a.	n.a.	40.3	5.2	0.9	0.5	16.3	12.0	16.8
Fine f.[c]	33.0	50.3	n.a.	n.a.	28.0	3.6	0.9	1.0	14.8	7.3	12.0
Heavy f[d]	8.9	96.0	n.a.	n.a.	8.3	1.1	0.2	0.1	4.0	2.5	3.0

[a]Bio. cont. represents the biomass content (bio carbon).
[b]MSW: energy waste collected from households.
[c]Fine f. fine fraction stream.
[d]Heavy f heavy fraction stream.
n.a.: not available.

Table 3. Consumption of energy to process MSW on MT plant to produce SRF.

Process	Unit	Energy consumption per tonne of input material
Inplant operations	KWh	70
Outplant operations	KWh	242

fraction, fine fraction and reject material streams were measured in the laboratory. Especially, ash content of heavy fraction stream was measured in the laboratory as high as 96 wt.%. It was owing to a high mass fraction of incombustible components (i.e. stone/rock, glass particles and metals) in these streams and especially in heavy fraction (see 'Composition of process streams'). Incombustible impurities considerably contribute to the overall ash load (Velis et al., 2011). Moisture content in fine fraction stream was measured higher in the laboratory as compared with other streams. This high moisture content was owing to the presence of bio waste (i.e. food waste) components in fine fraction. Fines are enriched with wet, biological degradable substances that contain a low calorific value (Rotter et al., 2004). In previous studies, a high moisture content in fine fraction streams is reported (Nasrullah et al., 2014a, 2014b).

The laboratory analysis does not include the metal fractions of process streams, but their mass fraction in each stream was known (see 'Composition of process streams') and thus the values of laboratory analysis parameters of process streams (given later in Table 3) were adjusted for the mass fraction of metals. The energy value of metals was considered to be inert (Biffaward Programme, 2003). The laboratory analysis results of input and output streams produced in SRF production plant, produced from MSW (energy waste collected from households) are given in Table 2.

Mass and energy flow balance in process streams of the SRF production process

The mass and energy flow in the various output streams of SRF production plant were analysed through mass and energy balances inside the process. The overall mass balance was calculated by weighing all streams (input and output). The overall energy balance of the input waste stream was calculated from the sum of energy content in the output streams.

Mass flow balance in process streams of the SRF production process. Overall mass flow balance of the SRF production process was established for a batch of 30 tonnes of MSW fed to MT waste sorting plant to produce SRF. All output streams produced from the input material was weighed to determine the overall mass flow balance of the SRF production process. The total amount of the input waste stream was recovered in the form of output streams with a minor (negligible) difference in mass. Overall mass flow balance of this SRF production process produced from MSW is shown in Figure 2.

Of the total input MSW, 72% was recovered in the form of SRF. SRF is the process product utilised for energy recovery and metals (ferrous/non-ferrous) recovered from this process are recycled. The streams of reject material, fine fraction and heavy fraction based on their composition are utilised partly for material recycling, energy recovery, environmental construction (landfill construction) and disposed to landfill.

Energy flow balance in process streams of the SRF production process. In MT waste sorting plant, the input waste material (i.e. MSW) was only subjected to mechanical separation and no material will be added to the process. This process was facilitated by the law of energy conservation. Based on the law of energy conservation, energy balance of the input waste material stream was calculated from the sum of energy content of the output streams.

Overall heating values of output streams were calculated by multiplying their NCV (MJ kg^{-1}, d) with their respective total masses. Heating values (MJ kg^{-1}, d) and moisture content of streams were measured in the laboratory (see Table 2) and their total masses were taken from the overall mass flow balance (see 'Mass flow balance in process streams of the SRF production

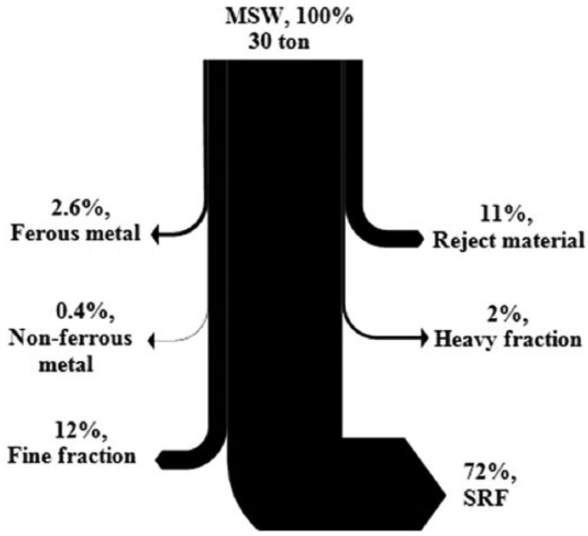

Figure 2. Mass flow balance in process streams of SRF production process: SRF produced from MSW (wet basis).
MSW: municipal solid waste; SRF: solid recovered fuel.

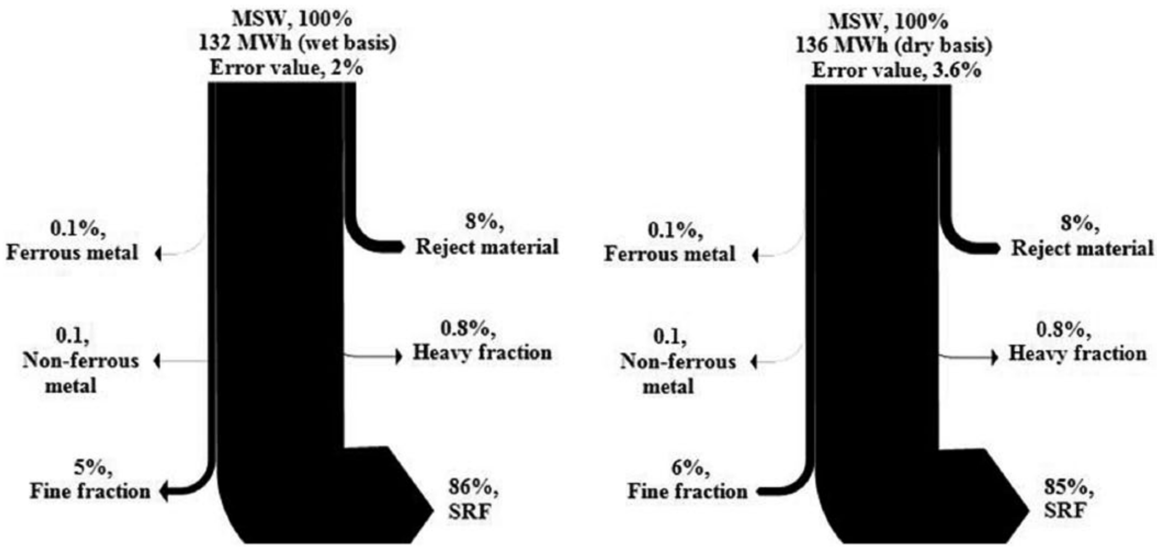

Figure 3. Energy flow balance in process streams of SRF production process: SRF produced from MSW.
MSW: municipal solid waste; SRF: solid recovered fuel.

process') of the SRF production process. The energy flow balance in process streams of the SRF production process was established for both wet and dry basis of material. The difference between measured and calculated energy value of the input energy stream is given as an error value. In the case of the energy balance made on wet basis, the calculated value of the input energy was 2% higher than the measured value, and for energy balance on dry basis, the calculated value of input energy was 3.6% lesser than its measured value. The energy flow balance in process streams of the SRF production process produced from MSW on wet and dry basis is shown in Figure 3.

Energy was partly recovered in the form of other streams (especially reject material and fine fraction) as well, but the fraction of energy contained by these streams was less than the SRF fraction. In addition, the reject material and fine fraction could not be utilised directly for energy recovery purposes. Energy content of ferrous metal and non-ferrous metal streams (shown in Figure 3) was owing to the small amount of combustible components (e.g. paper and cardboard, wood, plastics, etc.) in these streams and not owing to the metals, as the energy value of metals was considered as zero (Biffaward Programme, 2003).

Energy consumed in processing MSW to produce SRF

Energy consumed in processing the batch of 30 tonnes of MSW on MT waste sorting plant to produce SRF was divided into two operations:

- inplant operations;
- outplant operations.

Inplant operations included unit operations and sorting techniques used in MT plant, such as shredding, screening, magnetic and eddy current separators, wind shifters, NIR sorting unit, conveyor belts; dust extraction system and material handling machinery (e.g. wheel loaders and excavators). Outplant operations included the logistical means (transportation vehicles) used in collecting the batch of 30 tonnes of MSW from its collection points and to transport it to MT plant, and it also included the transportation of output process streams (i.e. SRF, metals, fine fraction, heavy fraction and reject material) to the customer's premises. Energy consumed by inplant operations was measured in terms of electricity (KWh) consumption, while energy consumed by outplant operations was calculated in terms of diesel consumption (in litres) and converted to electricity consumption (KWh). Energy consumed by inplant and outplant operations to produce SRF from MSW through MT is given in Table 3.

Energy consumed by outplant operations depended upon the distance covered (by transportation vehicles) to collect the batch of MSW, and to deliver the output streams to customer's premises. For this specific process, energy consumed by outplant operations was about 3.5 times of the energy consumed by inplant operations. For this specific process, the average route distance covered to collect the MSW from various collection points was 160 km, and to deliver the output stream to customer's premises was 120 km. The studies (such as primary energy used to generate the power consumed on this process, power generated from which fuel and description of plant used to generate the power) are not in the scope of this research. Energy consumed by the outplant operations in the case of SRF produced from MSW was significantly higher as compared with SRF produced from C&D waste and commercial and industrial waste (C&IW), respectively. The factor affected for this high energy consumption is discussed (see 'Comparison of results among three parts of study').

The energy consumed in terms of inplant and outplant operations to process MSW on MT plant was 312 $KWh\,t^{-1}$ of input material (see 'Energy consumed in processing MSW to produce SRF'). This energy refers to electrical energy. The energy produced from this MT process in the form of SRF was 5200 $KWh\,t^{-1}$ of SRF. This energy of SRF refers to fuel energy (not electrical energy) and was calculated based on mass flow and energy flow balance of the SRF production process (see 'Mass flow balance in process streams of the SRF production process' and 'Energy flow balance in process streams of the SRF production process'). The power (electrical energy) that can be produced from SRF based on the power plant efficiency. For example, in Finland efficiency (electricity, CHP case) for Lahti gasifier using SRF as fuel is given as about 31% (www.valmet.com). Based on this conversion the electrical energy of 1612 $KWh\,t^{-1}$ of SRF can be produced, which is about five times the energy consumed to process a unit tonne of MSW on MT plant to produce SRF. As mentioned ('Mass flow balance in process streams of SRF production process') the energy is also recovered partly from the output streams of reject material and heavy fraction streams based on their composition and streams of metals (ferrous and non-ferrous), and some other components form heavy fraction and reject material streams are recycled. The studies (such as which primary energy was used to generate the power consumed on this process, this power was generated from which fuel and description of plant and CO_2 emissions related with energy production used) are beyond the scope of this research.

Composition of process streams

Composition of process streams produced in SRF production plant was determined by manual sorting of their respective combined samples (see Table 1).

The input waste stream (i.e. MSW) was comprised of energy waste collected from households of municipality. Major components found in the input waste stream were, plastics (soft and hard), paper and cardboard and textile. Mass fraction of plastics (soft and hard), paper and cardboard, and textile in the energy waste stream was 28.6%, 24.5% and 8.8%, respectively, of its composition. A noticeable mass fraction of bio waste (especially food waste) was there in this input waste stream, i.e. 5% of its composition. The SRF produced from this energy waste was enriched in paper and cardboard, plastic (soft) and plastic (hard). Mass fraction of paper and cardboard, plastic (soft) and plastic (hard) in the composition of SRF was 30%, 19.6%, and 13 % respectively. Paper and card is a dominant fraction in SRF (Velis et al., 2011). Mass share of plastic (soft) was higher than that of plastic (hard) in the SRF stream. In the previous work, a higher mass fraction of plastic (soft) was found than that of plastic (hard) in SRF produced from C&IW (Nasrullah et al., 2014a). Other prominent components in the SRF stream were textile and wood. Stream of reject material was found to mainly consist of rubber material (highly chlorinated), plastic (mainly PVC-plastic), inert components (such as stone/rock and glass particles) and bio waste (especially food waste). A noticeable mass fraction of paper and cardboard and wood were found in the reject stream as well. These components of paper and cardboard and wood found in the reject stream were large (D_{95} > 250 mm) in their particle size or irregular in shapes. The composition of process streams produced in this SRF production plant produced from MSW (energy waste collected from households) is given in Table 4.

A very small mass fraction of components (such as paper and cardboard, plastic, wood, etc.) were found in the stream of metal (ferrous/non-ferrous). These components might be in contact with metals (i.e. in between or on top of metals) during the magnetic and eddy current separation. Stream of heavy fraction mainly consisted of heavy particles of waste components, such as stone/rock and metals. The fine fraction (D_{95} < 15 mm) stream was found to be mainly comprised of inert particles (such as stone/rock/sand/concrete and glass particles) and bio waste (food waste) and a small fraction of paper and cardboards, wood and plastic shredded to smaller particle size during primary shredding.

Table 4. Composition of process streams produced in MT waste sorting plant to produce SRF from MSW (energy waste collected from households) (wet basis).

Component	MSW[a] wt.%	SRF wt.%	Reject material wt.%	Ferrous metal wt.%	Non-ferrous metal wt.%	Heavy fraction wt.%	Fine fraction wt.%
Paper and cardboard	24.5	30.0	8.6	1.2	1.4	0.4	5.4
Plastic (hard)	12.0	13.0	16.0	2.3	1.6	6.4	2.8
Plastic (soft)	16.6	19.6	5.4	–	2.0	–	5.2
Textile	8.8	10.0	11.0	0.3	1.8	–	2.6
Wood	6.5	8.2	4.5	2.0	–	3.0	3.8
Bio waste	5.0	0.4	10.0	–	–	–	20.0
Rubber	4.8	2.2	24.0	–	–	–	2.5
Metal	4.6	0.5	1.0	92.0	90.0	10.0	3.0
Foam	1.8	2.6	0.5	0.8	0.6	–	6.5
Glass	3.2	0.7	7.8	–	–	–	22.2
Stone	2.6	–	6.0	–	–	78.2	16.8
Fines	9.6	12.8	5.2	1.4	2.6	2.0	9.2

[a]MSW: energy waste collected from households.
MSW: municipal solid waste; SRF: solid recovered fuel.

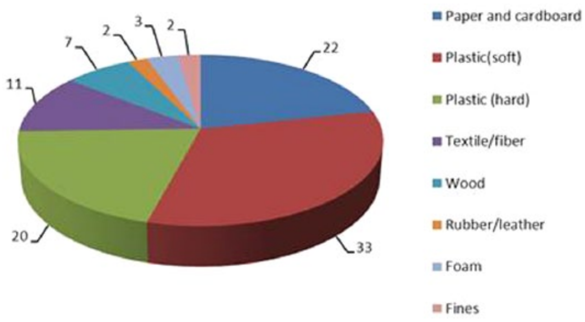

Figure 4. Energy (MJ kg^{-1}, a.r.) based composition of SRF produced from MSW (energy waste collected from households).

Composition of SRF produced from MSW (energy waste collected from households) based on the share of energy content of their components was calculated from their composition on mass basis and net calorific values of the components (described in Nasrullah et al., 2014a). A major portion of energy in the stream of SRF was contained by plastic (soft), plastic (hard) and paper and cardboard, respectively. The composition of SRF produced from MSW (energy waste collected from households), based on the share of energy content of its components, is given in Figure 4.

Plastic (soft) material found to contained higher energy content in SRF stream than paper and cardboard and plastic (hard). Other major components contributing to the energy content of SRF stream were textile and wood.

The carbon dioxide (CO_2, fossil) emission factor for SRF depends on the composition of it, i.e. the share of biomass and fossil carbon in it. Based on the carbon content (C), bio carbon content (C_{bio}), moisture content and heating value (a.r.) of the SRF, the carbon dioxide emissions were calculated. The values of these parameters are given in Table 3:

$$P_{CO2}\left(gCO_2 / MJ\right) = 1000 * 3.664 * C_{fos,\,ar} / H_{ar}$$

$$3664 * C * \left(1 - C_{bio,\,C}\right) * \left(1 - W\right) / H_{ar} \quad (1)$$

where, P_{CO2} is quantity of CO_2 (gCO_2/MJ), C_{fos}, is carbon (fossil) content, C is carbon content, C_{bio} is carbon (biomass) content, W is moisture content, H is heating value and ar is as received.

By putting the values of these parameters in equation (1):

$$P_{CO2}\left(t / TJ\right) = 40.0 \quad (2)$$

In equation (2), t is tonne and TJ (terra joule) is energy unit. The value of carbon dioxide (CO_2, fossil) emissions factor in (t TJ^{-1}) for the SRF produced from MSW (energy waste collected form households) was 40. The value of carbon dioxide (CO_2, fossil) emissions factor in (t TJ^{-1}) calculated for SRF produced from C&D waste was 28.3. This was owing to the high mass fraction of wood in the SRF stream produced from C&D waste (Nasrullah et al., 2014b).

Material balances

Material balances included the mass balances of components of input waste stream in the output streams of SRF production plant. Based on these material balances, the mass flow of various components of input waste stream was analysed in the output streams. Material balances were calculated from composition of input and output streams (see 'Composition of process streams') and overall mass flow balance of SRF production plant (see 'Mass flow balance in process streams of the SRF production process'). The mass of each component in every stream was calculated by multiplying the mass fraction of that component in the stream (composition of stream) with the total mass of that stream (overall mass flow balance of SRF production plant). The material balances of paper and cardboard, wood, plastic (soft), plastic (hard), textile and rubber in the input and output streams of MT-based SRF production plant is shown in Figure 5. Difference in the calculated mass of a component in the input stream and sum of the mass of the same component in the output streams is given as a loss value. In some streams a minor mass fraction of components (negligible quantity compared with its input mass) is shown as not found in those streams. Sorting of components of input waste stream into various output streams was based on the fact that the recyclable material (ferrous/non-ferrous metal), non-combustibles or harmful materials (stone/rock, glass, PVC plastic and high chlorinated material such as rubber) were sorted out into separate small streams to produce a high yield of controlled quality SRF stream. In the SRF production plant, sorting processes are designed based on material properties, e.g. particle size (screening), density/weight (air classifier), magnetic properties (magnetic separation) and infra-red (IR)-spectra (NIR sorting).

A very high mass fraction of paper and cardboard, wood and plastic (soft) was recovered in the SRF stream of their respective input masses. Mass fraction of paper and cardboard, wood and plastic (soft) recovered in the SRF stream was 88%, 90%, and 85%, respectively, of their respective input masses to MT plant. Similarly, a high mass fraction of textile was also recovered in the SRF stream, i.e. 82% of its total input mass. A small mass fraction of these components was also found in the reject material and fine fraction streams. Small mass fraction of combustibles (paper and cardboard, wood, etc.) found in the fine fraction was owing to the shredding of these components to a smaller particle size (<15 mm) during primary shredding of the input waste stream. Mass fraction of plastic (hard) recovered in the SRF stream was lesser than that of plastic (soft), as a considerable mass fraction of plastic (hard) was found in the reject material stream. Components of plastic (hard) found in the reject steams were mainly PVC-plastic. A high mass fraction of rubber was there in the reject stream, i.e. 55% of its input mass. Rubber material found in the reject stream contained high chlorine content. Waste material ends up in reject streams after being passed from a NIR sorting unit. In this waste sorting process, a NIR sorting unit was set on positive sorting (i.e. sorting of the combustibles from non-combustibles). Combustibles (paper and cardboard, non-PVC plastic and wood, etc.) were picked up by a NIR sorting unit to put them in the SRF stream and the rest of the material was separated as reject material (i.e. non-combustibles such inters, PVC plastics and high chlorinated rubber, etc.). NIR technology reduces chlorine content to produce a high quality SRF (Glorious, 2012). Material in the reject stream is utilised partly for energy recovery (wood and paper and cardboard), material recycling (metals, plastics and rubber) and landfill construction and disposed to landfill (stone/rock and other inert material). A major fraction of bio waste (food waste) of its total input mass was found in fine fraction, but a considerable portion of it was also found in reject material stream. Most of the bio waste (food waste) was shredded to fine fraction (<15 mm) in the primary shredding and was screened out to a fine fraction stream.

In this SRF production process, very high mass fraction of combustible components (especially paper and cardboard, plastics and wood) of input waste stream was recovered in the form of a SRF stream. It was observed that proper particle size distribution, particle shape and moisture content of the input waste stream of MSW (energy waste collected from households) was the reason for this high recovery of combustibles in the SRF stream.

Comparison of results among three parts of study

In the case of SRF produced from MSW, the recovery of material and energy in the form of SRF was higher as compared with SRF produced from C&IW and C&D waste, respectively. The recovery of major components, i.e. paper and cardboard, plastics (soft and hard) and wood was also higher in the SRF stream produced from MSW, as compared with SRF produced from C&IW and C&D waste, respectively. In these SRF production processes, the distribution of the components (paper and cardboard, plastics and wood) in various output streams determined the yield and quality of the SRF stream. In the case of SRF produced from C&IW and C&D waste, respectively, a high mass fraction of key combustibles (i.e. paper and cardboard and wood) were found in the reject material stream, which were supposed to be in the SRF stream. But in the process of SRF produced from MSW, most of the mass fraction of components (i.e. paper and cardboard and wood) was recovered in the SRF stream and a small fraction was found in the other streams, which increased the yield of SRF. It was observed that in the processes of SRF produced from C&IW and C&D waste, respectively, the components of paper and cardboard and wood found in the reject material streams were either large in particle size (>250 mm), irregular in shape (paper and cardboard in bundle form) or highly moist. Whereas, in the process of SRF production from MSW, the components (paper and cardboard and wood) were found to be relatively better in size distribution, shape and less moist. The particle size, shape and moisture content of waste components were connected with the nature of the input waste stream, i.e. C&IW, C&D waste and MSW.

In the case of SRF produced from MSW, the energy consumed by the outplant operations was 1.86 times and 2.42 times higher than the energy consumed by the outplant operations for SRF produced from C&IW and C&D waste, respectively. The major

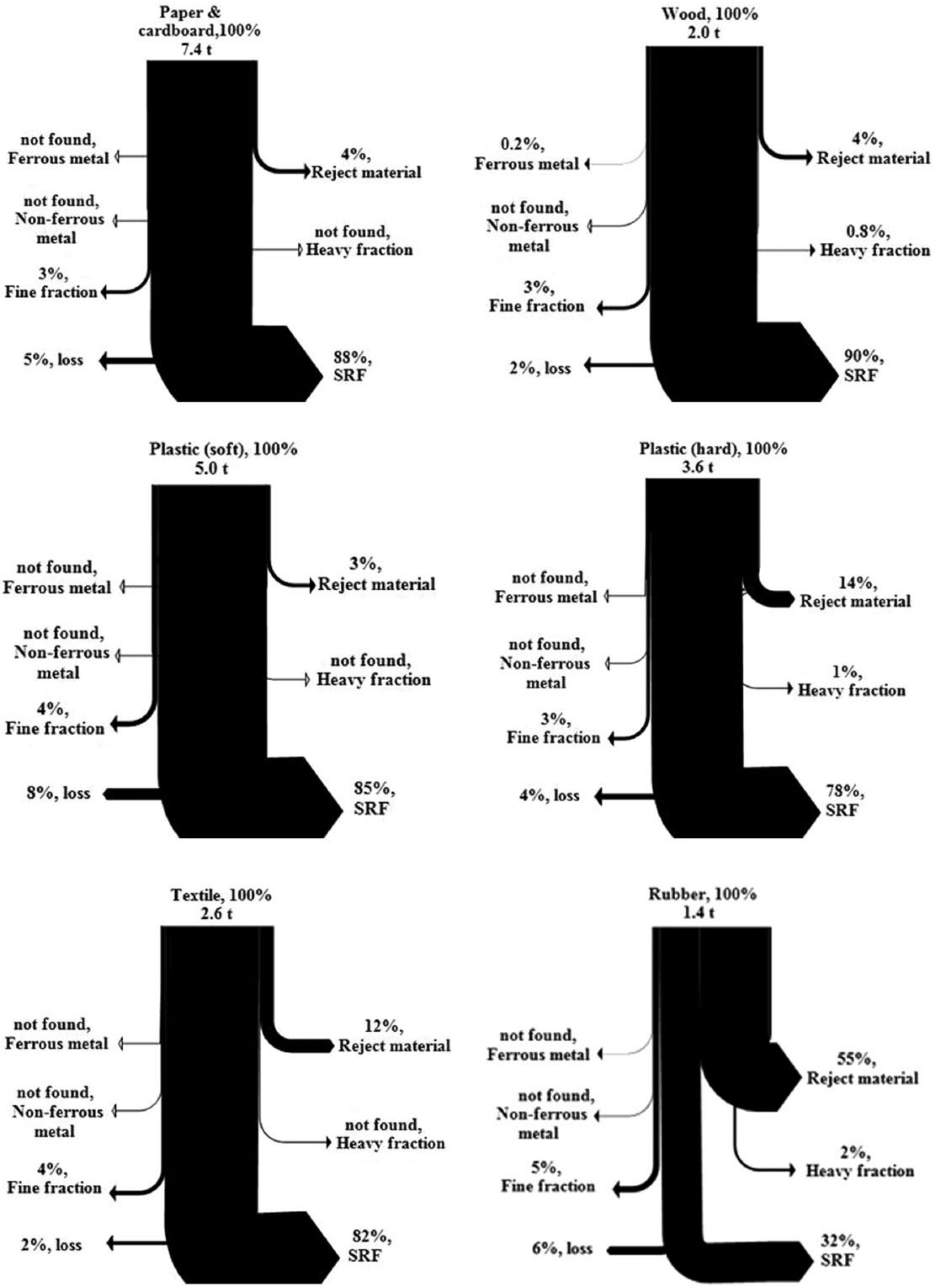

Figure 5. Material balances of input waste components in the output streams of SRF production plant produced from MSW (energy waste collected from households) (wet basis).
SRF: solid recovered fuel.

Table 5. Comparison of results for SRF produced from three different types of waste streams.

Results		SRF produced from C&IW Part 1[a]	SRF produced from C&D waste Part 2[b]	SRF produced from MSW Part 3[c]
SRF recovery (wt. %)		62	44	72
Energy recovery (MWh, %)		75	74	86
Energy consumption (KWh)	Inplant operations	60	50	70
	Outplant operations	130	100	242
Material recovery of major components (wt.%)	Paper and cardboard	72	82	88
	Plastic (soft)	88	84	85
	Plastic (hard)	70	68	78
	Wood	60	72	90
	Textile	58	70	82

[a]The results published in the part 1 (Nasrullah et al., 2014a).
[b]The results published in the part 2 (Nasrullah et al., 2014b).
[c]The results from this article (i.e. Part 3).
C&D waste: construction and demolition waste; C&IW: commercial and industrial waste; MSW: municipal solid waste; SRF: solid recovered fuel.

factor of this difference was fuel consumption by trucks/lorries in order to collect the input waste material from the collection points. In the case of collecting C&IW and C&D waste, less fuel was consumed (as waste material was collected from main commercial and demolition locations), whereas in the case of MSW, the fuel consumption was high (as waste material was collected from different small household collection points of municipality) (Table 5).

After investigation of the whole waste series (i.e. SRF production from C&IW, C&D waste and MSW), there are two most important and influencing factors identified affecting SRF production in respect to energy recovery. Based on the results obtained from these material balances, the most critical components identified that affected the yield of SRF were mainly paper and cardboard, wood and plastics, and to some extent textile as well. The first important factor identified is the mass flow of these components in various output streams of the SRF production process was found to be affected by their particle size, density/weight, shape and moisture content. Based on these findings, it is suggested here that better particle size distribution in primary shredding in terms of particle size and shape, and by adding a drying operation in the process, could have improved the sorting efficiency of various sorting processes (especially air classifier) to enhance the yield of the SRF production process in order to recover higher energy from input waste stream. This suggestion is based on the fact that a considerable mass fraction of combustibles (i.e. paper and cardboard, wood, textile and non-PVC plastics) were found in reject the material stream having a large particle size (>250 mm), irregular shape (paper and some textile in a rolled bundle form) and heavy moisture content (heavy in weight). The addition of a drying operation is to be dealt with the energy and cost efficiency and to handle with the evaporated water and pollutants in the process. The most relevent option is biodrying as the bioprocess operation in mechanical biological treatment (MBT) plants. Traditional drying using fossil fuel is not used that much due to high cost.

The second most important factor is that in order to enhance the yield of the SRF production process, it is very important to balance mass flows of the plant. This could be done by (first of all) careful feeding of input waste by excavator (not to try to feed as much as possible). Then adjusting processes so that the mass flows divided to the processes are in line with the designed capacities of machines, not too much or sudden peaks of material coming to any of the sorting processes (especially air classifiers and NIR sorting units). Continuous maintenance (checking measurements of unit operations) is also important (e.g. keeping clean air nozzles of NIR units), ensure that machines are working properly and setups are correct.

Conclusion

In this work, SRF was produced from MSW through MT. The stream of MSW used as an input waste stream to produce SRF was energy waste collected from households. This process recovered a high yield of useful material in the form of SRF to be utilised for energy recovery.

Of the total input waste material to the MT waste sorting plant, 72% was recovered in the form of SRF and 3% as metals (ferrous/non-ferrous). In terms of energy recovery, 86% of the total input energy content of input waste material to MT plant was recovered in the form of SRF. Energy consumed in processing the input waste stream to produce SRF through MT was calculated in terms of inplant operations (i.e. unit operations/sorting techniques used in MT plant) and outplant operations (i.e. logistics involved in collecting the MSW from its collection points and to deliver the output streams, such as SRF and others to customer's premises). For this specific process, energy consumed on outplant operations was about 3.5 times the energy consumed on inplant operations.

In the composition of SRF produced from energy waste collected from households, paper and cardboard, plastic (soft), plastic (hard) and textile were found as the major components. Mass fraction of these components was 30%, 19.6%, 13% and 10%, respectively, in the SRF composition (wet basis). In the composition of reject stream, rubber and plastic (PVC) were the major components and other prominent components in this stream were inert material (i.e. stone/rocks and glass particles).

Based on the results obtained from material balances of SRF production processes, it was identified that paper and cardboard, wood and plastics were the most critical components of input waste streams that affected the yield and quality of SRF. The mass flow of these components in various streams of SRF production process was found affected by their particle size, particle shape and moisture content, which was connected with the nature of input waste stream.

Declaration of conflicting interests

The authors declare that there is no conflict of interest.

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Reference

Biffaward Programme on Sustainable Resource Use (2003) Thermal methods of municipal waste treatment. Available at http://www.massbalance.org/downloads/projectfiles/1826–00237.pdf (accessed February 2014).

Council Directive 1999/31/EC on the landfill of waste. *Official Journal of the European Communities*. Available at http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31999L0031&from=EN (accessed July 2014).

Dunnu G, Maier J and Scheffknecht G (2010a) Ash fusibility and compositional data of solid recovered fuels. *Fuel* 89: 1534–1540.

Dunnu G, Maier J and Scheffknecht G (2010b) Drag coefficient of solid recovered fuels (SRF). *Fuel* 89: 4053–4057.

Garg A, Smith R, Hill D, et al. (2009) An integrated appraisal of energy recovery options in the United Kingdom using solid recovered fuel derived from municipal solid waste. *Waste Management* 29: 2289–2297.

Glorious T (2012) Production and use of solid recovered fuels – developments and prospects. In: *Waste management and energy*, conference, Berlin, 30 -31 December 2012. Available at: http://erfo.info/fileadmin/user_upload/erfo/documents/other-projects/Berlin_Glorius_January_2012.pdf (acessed on 8 December 2014).

Hansen PFB, Andersen KH, Wieck-Hansen K, et al. (1998) Co-firing straw and coal in a 150-MWe utility boiler: in situ measurements. *Fuel Process Technology* 54: 207–225.

Luoranen M and Horttanainen M (2007) Feasibility of energy recovery from municipal solid waste in an integrated municipal energy supply and waste management system. *Waste Management & Research* 25: 426–439.

Montané D, Abelló S, Farriol X, et al. (2013) Volatilization characteristics of solid recovered fuels (SRFs). *Fuel Processing Technology* 113: 90–96.

Nasrullah M, Vainikka P, Hannula J, et al. (2014a) Mass, energy and material balances of SRF production process. Part 1: SRF produced from commercial and industrial waste. *Waste Management* 34: 1398–1407.

Nasrullah M., Vainikka P, Hannula J, et al. (2014b) Mass, energy and material balances of SRF production process. Part 2: SRF produced from construction and demolition waste. *Waste Management*. 34: 2163–2170.

Pinto F, André RN, Carolino C, et al. (2014) Gasification improvement of a poor quality solid recovered fuel (SRF). Effect of using natural minerals and biomass wastes blend. *Fuel* 117B: 1034–1044.

Rada EC and Andretottola G (2012) RDF/SRF: which perspective for its future in the EU. *Waste Management* 32: 1059–1060.

Rada EC and Ragazzi M (2014) Selective collection as a pretreatment for indirect solid recovered fuel generation. *Waste Management* 34: 291–297.

Ragazzi M and Rada EC (2012) RDF/SRF evolution and MSW bio-drying. *WIT transaction on Ecology and the Environment* 163: 208.

Rotter VS, Kost T, Winkler J, et al. (2004) Material flow analysis of RDF-production processes. *Waste Management* 24: 1005–1021.

Umberto A and Fabrizio DG (2014) A waste management planning based on substance flow analysis. *Resources, Conservation and Recycling* 85: 54–66.

Vainikka P, Enestam S, Silvennoinen J, et al. (2011) Bromine as an ash forming element in a fluidised bed boiler combusting solid recovered fuel. *Fuel* 90, 1101–1112.

Velis C, Wagland S, Longhurst P, et al. (2011) Solid recovered fuel: Influence of waste stream composition and processing on chlorine content and fuel quality. *Environmental Science and Technology* 46: 1923–1931.

Velis C, Wagland S, Longhurst P, et al. (2013) Solid recovered fuel: Materials flow analysis and fuel property development during the mechanical processing of biodried waste. *Environmental Science & Technology* 47: 2957–2965.