Department of Biotechnology and Chemical Technology

Material and energy balance of solid recovered fuel production

Muhammad Nasrullah

Aalto University

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Abstract

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Abstract

The quality of solid recovered fuel (SRF) holds the key to its market demand and utilization for power production. However, the lack of consistency in the quality and availability of SRF may limit its applications in power producing industries. In the SRF production, proper sorting of input waste's components into the relevant output streams is a decisive factor in defining the quality and yield of the SRF.

The objective of this research work was to establish the material and energy balance of SRF production based on an in-depth analysis and detailed evaluation of physical and chemical characteristics of the input and output streams and waste components produced in industrial-scale SRF production. The SRF was produced from three different types of waste materials: commercial and industrial waste (C&IW), construction and demolition waste (C&DW) and municipal solid waste (MSW).

In the case of SRF produced from MSW, higher yields of material were recovered in the form of SRF as compared with that recovered from C&IW and C&DW. Of the MSW input to the process, 72 wt. % was recovered as SRF, equivalent to 86 % energy recovery. In the case of SRF produced from C&IW, a higher mass fraction of the input chlorine (Cl), lead (Pb) and mercury (Hg) was found in the SRF as compared with the SRFs produced from C&DW and MSW, namely 60 %, 58 % and 45 %, respectively. The SRF produced from C&DW was found to contain the lowest mass fraction of the input chlorine, lead and mercury in comparison with the SRFs produced from C&IW and MSW, namely 34%, 8% and 30%, respectively. In each case of the SRF production, a higher mass fraction of the input cadmium (Cd) was found in the SRF than in the other output streams. Among the waste components, rubber, plastic (hard) and textile (synthetic type) were identified as the potential sources of polluting elements and potentially toxic elements (PTEs). In C&IW, C&DW and MSW, rubber was measured to contain 8.0 wt. %, 7.6 wt. % and 8.0 wt. % of chlorine, respectively. In C&DW, plastic (hard) and textile (especially synthetic type) were measured to contain 7.0 wt. % and 3.8 wt. % of chlorine respectively.

The results of this thesis can be used by the SRF manufacturers and users in order to enhance and implement their understandings about the quality and yield of SRF and the research institutes/organisations to make use of the generated data, in waste management and waste-to-energy related modelling and decision making tools.

Keywords Solid recovered fuel, material and energy balance, polluting and potentially toxic elements

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‘’In the name of ALLAH, most Gracious, most Compassionate”.
‘’All the praises be to ALLAH, the Lord of the worlds”.

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I hope this thesis provides a step forward in the knowledge and science concerning solid recovered fuel, specifically about the material and energy balance of solid recovered fuel production. The thesis mainly consists of experimental work based measurements, analysis and interpretation of results regarding the in-depth physical and chemical characterisation of input and output streams and waste components produced in commercial scale solid recovered fuel production.

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Muhammad Nasrullah
Espoo, November 2015

List of Abbreviations and Symbols

a.r.	As-received basis of material
C&DW	Construction and demolition waste
CEN	European Committee for Standardization
CHP	Combined heat and power
CHNSO	Carbon, Hydrogen, Nitrogen, Sulphur, Oxygen
C&IW	Commercial and industrial waste
D_{95}	Top nominal size
d.	Dry basis o material
GCV	Gross calorific value
HHW	Household waste
ICP-MS	Inductively coupled plasma mass spectrometry
ICP-OES	Inductively coupled plasma optical emission spectrometry
MBT	Mechanical biological treatment
MFA	Material flow analysis
MSW	Municipal solid waste
MT	Mechanical treatment
NCV	Net calorific value
NIR	Near-infrared
PTEs	Potentially toxic elements
PVC	Polyvinyl chloride
RDF	Refuse derived fuel
SRF	Solid recovered fuel
wt. %	Weight %

List of Publications

The thesis is based on the compilation of the following publications which are referred to by the corresponding numbers:

I. Nasrullah, M., Vainikka, P., Hannula, J., Hurme, M., Kärki, J., Mass, energy and material balances of SRF production process. Part 1: SRF produced from commercial and industrial waste, *Waste Management*, volume 34, Issue 8, August 2014, Pages 1398 – 1407.

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III. Nasrullah, M., Vainikka, P., Hannula, J., Hurme, M., Kärki, J., Mass, energy and material balances of SRF production process. Part 2: SRF produced from construction and demolition waste, *Waste Management*, volume 34, Issue 11, November 2014, Pages 2163 – 2170.

IV. Nasrullah, M., Vainikka, P., Hannula, J., Hurme, M., Koskinen, J., Elemental balance of SRF production process: Solid recovered fuel produced from construction and demolition waste. *Fuel,* volume 159, Issue 1, November 2015 Pages 280 – 288.

V. Nasrullah, M., Vainikka, P., Hannula, J., Hurme, M., Kärki, J., Mass, energy and material balances of SRF production process. Part 3: SRF produced from municipal solid waste, *Waste Management & Research*, volume 33, Issue 2, February 2015, Pages 146 – 156.

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Author's Contribution

I. The author planned and designed the experimental work along with co-authors, conducted the experimental work, analysed the results and wrote the paper.

II. The author was involved in planning the experimental work with co-authors. The author analysed the results, performed the calculations of data generated from the experimental work's measurements and wrote the paper.

III. The author carried out and planned the experimental work, analysed the results obtained from the experimental campaign, performed the calculations and wrote the paper.

IV. The author planned the experimental work along with the co-author, performed the analysis and calculations of the results obtained from the experimental work and wrote the paper.

V. The author conducted the experimental work as designed and planned, analysed the results of the experiments, performed the calculations and wrote the paper.

VI. The author planned the experimental work along with the co-authors, analysed the results, performed the calculations of the experimental data and wrote the paper.

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1. Introduction

1.1 Background

The field of ‘waste’ is of great importance all around the world. Even in the developed countries, the waste sector is somewhat of a grey area. The amount of waste is increasing dramatically around the globe due to rapid urbanization, population growth and changes in lifestyle. The global generation of municipal solid waste (MSW) is likely to reach 2.2 billion tonnes per year by 2025 (World Bank, 2012). This brings more pressure, responsibility as well as opportunities for the waste management sector.

Proper waste management is vital, not only to deal with the issues related to the environmental and health impact on our society, but also in ensuring resource efficiency and sustainable economic growth. A sustainable modern integrated waste management system should include effective waste prevention, effective source separation practices, and all the possible recycling activities without entailing excessive resource consumption, efficient biological treatments of organic fractions and energy recovery from materials that cannot be efficiently recycled (Brunner and Rechberger, 2014; Bosmans et al., 2013; Arena and Gregorio, 2014). In the EU, waste prevention and management legislation is summarized in a five-step Waste Hierarchy (European Commission, 2008). In this hierarchy, waste prevention is the best option, followed by reuse, recycling and recovery, with disposal such as landfill as the last option. It is recognized that in a fully sustainable waste management system no single process is suitable for all waste streams (McDougall et al., 2001; Brunner, 2010; Ionescu et al., 2013; Santibañez-Aguilar et al., 2013; Menikpura et al., 2013). The EU Waste Framework Directive also notes that, if supported by life cycle thinking, options lower down the hierarchy may be adopted in some circumstances, if they provide a better environmental solution in terms of waste management (European Commission, 2008).

Globally, solid waste disposal is responsible for about 3 - 4% of anthropogenic greenhouse gas (GHG) emissions (IPCC, 2006). In the EU-27, the waste management sector was responsible for 3% of the total GHG emissions generated in 2011 and solid waste disposal accounted for 74% of all the waste management greenhouse gas (GHG). In Finland, in 2011, waste management had a 3% equivalent share of total GHG emissions, and the share of waste disposal from waste management GHG emissions was 84% (United Nations, 2013; Eurostat, 2013). Methane is the most significant GHG emission source from waste landfills. According to the Finnish government decree (EU regulations) on landfills (Eurostat, 2013), waste containing over 10% biodegradable materials measured by the total organic carbon or ignition loss is banned from landfill; this is due to come into force on 1 January, 2016.

The EU-25 annually generated 241 million tonnes of MSW (Eurostat, 2009), roughly half (49%) of which is landfilled (Kloek and Jordan, 2005) and 17% is incinerated. According to the EU, the diversion of municipal solid waste (MSW) from landfilling to composting, recycling and energy recovery could mean a reduction from 40 to over 100Mt CO_2 equivalents per year; and for the EU-15, this corresponded to 29% of the total GHG reduction target under the Kyoto protocol (European Parliament, 2006; Commission of the European Communities, 2005). Theoretically, with an average electric efficiency of 25% (Gohlke and Martin, 2007) and having a lower heating value of 11 MJ/kg (IPCC Bureau, 2006; U.S. Department of Energy, 2007), 184 TWh of electricity could be generated through MSW combustion, which corresponds to 5.7% of the total electricity generation in the EU-25 (Eurostat, 2009). In comparison, the US generates 250 Mt of MSW annually, of which landfilling accounts for 54% and incineration 13% (United States Environmental Protection Agency, 2008).

High efficiency power generation from waste through gasification or combustion effectively requires knowledge of the physical and chemical properties of the waste (as fuel). In Europe, energy recovery from waste has been adopted as one of the sustainable waste management options to reduce the amount of non-hazardous waste for landfilling. The recovery of energy from MSW is essential in order to achieve the goals set for waste utilization. Direct waste incineration has several issues, for example it requires the construction of dedicated incineration plants, besides having direct environmental impacts and poor public acceptance. This effectively demands the production of solid recovered fuels (SRFs). The use of solid recovered fuel (SRF) and its development has become an interesting option as a suitable alternative for fossil fuels in already existing power production plants. Significant work has been allocated to downstream system research, i.e. thermal treatment; however, comparatively, much less research effort has been put into the fuel preparation stage, and scientific publications on the subject are very few.

The emphasis of this research work is on the comprehensive study of SRF production, based on an in-depth evaluation and detailed characterisation of the input and output streams of material produced in commercial-scale SRF production. The SRF production process is thoroughly examined, and each fuel preparation stage is closely studied. The quality of SRF is comprehensively analysed and presented in terms of the mass, energy, material and elemental balances of SRF production. The SRF studied was produced on industrial scale from three different types of waste material by mechanical treatment (MT).

In this research work, three different types of waste material were used for the production of SRF separately. These waste materials were collected from the metropolitan area of Helsinki region in Finland. The Helsinki region includes four cities; Helsinki, Vantaa, Espoo and Kauniainen with population of about 1.1 million. These types of waste material colleted and used to produse SRF are;

- Commercial and industrial waste (C&IW): It is solid waste generated by the commercial and industrial sector (shopping centres, offices, warehouses, logistics, manufacturing organizations and retail outlets, etc.) and institutions (educational institutions, medical centres' offices
- and government offices, etc.). It mainly contains paper & cardboards, plastic, textile, wood, rubber, metal and inert (stones and glass).
- Construction and demolition waste (C&DW): It is solid waste generated or produced during the destruction/demolition of buildings. The major components of C&DW were building material (stone, rock, concrete, and sand), wood, metal and plastic. In Finland, C&DW contains more combustibles (especially wood) as compared with C&DW in central Europe.
- Municipal solid waste (MSW): the stream of MSW used here was energy waste collected from households. This energy waste (fraction) was not subject to recycling but to energy recovery. The energy waste (fraction) was source-separated at the household level and contained more than 75 wt. % of energy-related waste components, for example, paper & cardboard, plastics, textile, wood, rubber and foam material and a small wt. % of non-energy waste related components such as inert material (metals, glass, stones) and food waste due to some false sorting.

The detailed physical and chemical characterisations of C&IW, C&DW and MSW are described in Chapters 3, 4 and 5 respectively.

1.2 Solid Recovered Fuel (SRF)

Solid recovered fuel (SRF) is prepared from non-hazardous waste to be utilized for energy recovery in incineration/co-incineration plants and meeting the classification and specifications requirements laid down in CEN standards (EN 15359). Here 'prepared' means processed, homogenized and upgraded to a quality that can be traded amongst producers and users. In the mentioned context here incineration mainly involves combustion and gasification processes.

SRF is becoming a significant contributor to the agenda of international resource and energy efficiency (Velis et al., 2013). SRFs are seen as important contributors to a sustainable EU waste management and contribute to the security of energy supply for the EU, representing a significant potential storable source of indigenous energy (Lund, 2007; Caspary et al., 2007). In Europe, the SRF trade is a reality (Velis and Copper, 2013) and is becoming a major route for energy from waste throughout Europe (Velis et al., 2011). China and Korea are fast-developing economies that are considering widespread use of SRF in co-combustion (Carone, 2008; Choi et al., 2012; Lorber and. Ragoßnig, 2012). One of the major advantages of SRF is that it possesses the biogenic content of the initial waste stream, which is carbon dioxide (CO_2) neutral and is an alternative energy source that can partly replace the fossil fuels in heat and power producing industries.

In Europe, SRF is produced from different types of waste streams, for example household waste (HHW), commercial and industrial waste (C&IW), construction and demolition waste (C&DW) and from some selected streams of waste material (Velis et al., 2013; Rada and Ragazzi, 2014; Lorber and Ragoßnig 2012). In Europe, SRF is produced in mechanical treatment (MT) or mechanical biological treatment (MBT) plants (Ragazzi and Rada, 2012; Velis et al., 2011; Ionescu et al., 2013; Rada and Ragazzi, 2014). In MT plants, various unit operations/sorting techniques are applied (for example, shredding, screening, magnetic and eddy current separation, pneumatic separation, optical sorting and near-infrared (NIR) sorting) to sort input waste material into various output streams to produce SRF.

SRF is used as fuel/co-fuel in cement kilns, lime kilns, coal-fired power plants, industrial boilers and gasification and combustion based combined heat and power (CHP) plants for the production of energy (power and heat), which reduces the amount of waste going to landfill and replaces fossil fuels to a significant extent. In Europe, the largest CHP and power plant capacities for SRF utilization are currently in Germany, Finland and Sweden (EN15443). The estimated possible use of SRF in the long run (EU-27, 2020) in cement kilns, coal-fired power plants and CHP plants is 24-43 million tonnes/year (ERFO).

In the last years, the term used for the fuel generated from MSW has undergone some changes. In the technical literature, the most common name used to be refuse-derived fuel (RDF), before the more recently adopted term, solid recovered fuel (SRF). These changes are driven by new regulation and accompanying standards. By the early 1990s, an initial disaster cycle for RDFs was effectively closed and the term ended up denoting a low-quality fuel or absence of quality checks (Velis and Copper, 2013). Due to the high concentrations of chlorine and heavy metals, RDFs could not create enough market demand (Rotter et al., 2004). The challenges around RDF at that time were not significantly different to those of today (Velis and Copper, 2013). SRF is clearly distinguished from RDF. The major difference is that SRF is manufactured in compliance with CEN standards (EN15359), whereas RDF is not. The principle for distinguishing SRF from RDF is shown in Figure 1.

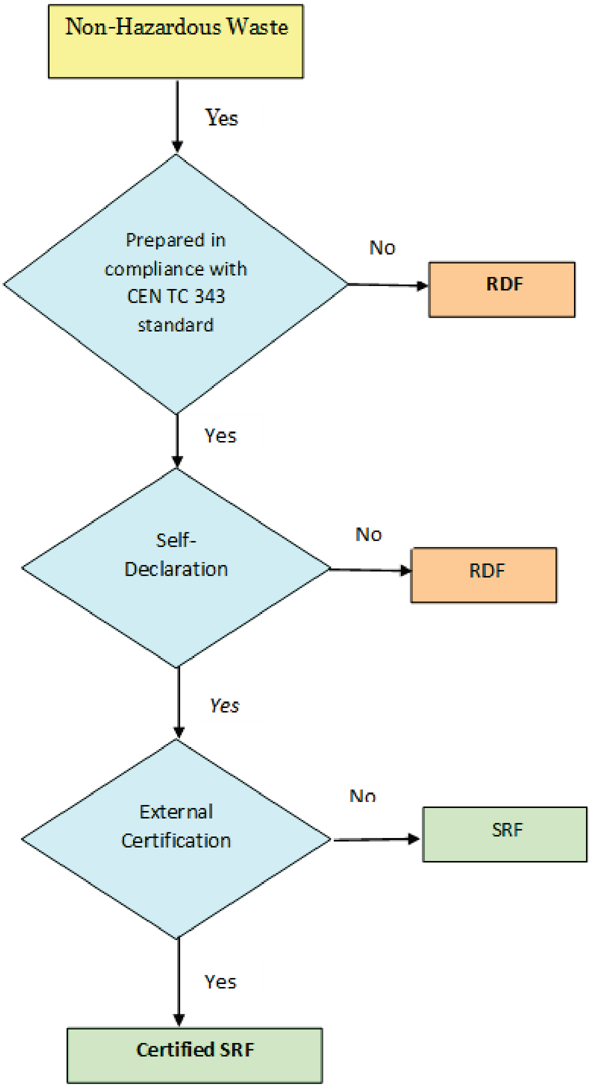


Figure 1: Principle for distinguishing SRF from refuse-derived fuel (ERFO)

1.3 Classification of SRF

The classification system for SRF (EN 15359) is based on three important fuel properties: an economic parameter (net calorific value), a technical parameter (chlorine content) and an environmental parameter (mercury content). The classification system for SRF is given in Table 1.

The fuel properties are:

- Mean value for net calorific value (NCV; as-received basis)
- Mean value for chlorine content (dry basis)
- Median and 80th percentile values for mercury content (as-received basis)

Table 1: Classification systems for solid recovered fuel (EN 15359)

Classification property	Statistical measure	Unit	Classes				
			1	2	3	4	5
Net calorific value (NCV)	Mean	(MJ/kg)	≥ 25	≥ 20	≥ 15	≥ 10	≥ 3
Chlorine (Cl)	Mean	% (d)	≤ 0.2	≤ 0.6	≤ 1.0	≤ 1.5	≤ 3
Mercury (Hg)	Median	mg/MJ (ar)	≤ 0.02	≤ 0.03	≤ 0.08	≤ 0.15	≤ 0.50
	80th percentile	mg/MJ (ar)	≤ 0.04	≤ 0.06	≤ 0.16	≤ 0.30	≤ 1.00

Only those fuels that are derived from non-hazardous waste and meet the CEN standards for SRF can be classified as SRFs. However, the classification of SRFs may not be sufficient for the user. The user has to have a further detailed description of the fuel based on general/specific requirements. Relevant fuel properties can be further specified between the user and producer of SRF. Some critical fuel properties need to be specified, whereas others can be described voluntarily or upon user request (EN 15359).

1.4 Quality of SRF

The quality of SRF is key for its future market demand and utilization as a mainstream fuel, especially in power-producing industries. The quality of SRF is often defined in terms of homogeneity (composition), energy efficiency (heating value) and environmental and technical parameters (concentration of a certain element, especially chlorine and heavy metals). Quality assurance for SRF implies that the heating value and concentration of chlorine (Cl) and mercury (Hg) are as per the CEN standards for SRF (EN 15359) and moreover, the concentration of heavy metals is to be kept as low as possible. For SRF to be accepted as a replacement for conventional fuels (fossil fuels), especially in the power generation industry, it is of utmost importance to achieve good quality in terms of homogeneity, energy efficiency and environmental and technical parameters. An overview of the validation programme regarding technical specifications (TSs) to guarantee the quality of SRF and examination of the implementation of quality management of the whole SRF production process is presented in "Quality management organization, validation of standards, developments and inquiries for solid recovered fuels" (Gawlika et al., 2007).

In Europe, SRF is produced from various types of non-hazardous waste material such as commercial and industrial waste (C&IW), construction and demolition waste (C&D waste) and household waste (HHW) and sewage sludge and some other selected streams of waste material. In an MT or MBT SRF production plant, based on the unit operations/sorting techniques, the input waste stream is divided/classified into various output streams such as fine fraction, ferrous metal, non-ferrous metal, heavy fraction, reject material and SRF as process product.

The mass flow of the input waste stream components (paper & cardboard, plastic, textile, wood, rubber etc.) in the relevant output streams of SRF production plays a decisive role in defining the quality of SRF. In an SRF production plant, there is a strong connection between the proper sorting of input waste stream components into the relevant output streams and the quality and yield of SRF. The sorting of the input waste stream components into the output streams is significantly affected by the properties of the components (i.e. in terms of moisture content, particle size distribution and particle shape of the components) (Nasrullah et al., 2014a; Nasrullah et al., 2015b). In SRF production, unit operations/sorting techniques and their arrangements (in terms of plant flow sheet/configuration) have a significant impact on the quality of SRF. In MT/MBT SRF production plants, the functionality in terms of capacity and the performance of air classifier and near-infrared (NIR) sorting units play a vital role in the proper sorting of the combustible/non-combustible components of the input waste stream into SRF and other than SRF streams (i.e. reject material and heavy fraction).

A low confidence level in the quality, limits the applications of SRF as a mainstream fuel. An in-depth knowledge of the physical and chemical characteristics of the waste components and, input and importantly, the output streams of SRF production is essential for the understanding of SRF quality. Here, in this context, the physical characteristics include composition, appearance (in terms of particle size, shape and colour of components), weight/density and moisture content, and the chemical characteristics include heating value and elemental (i.e. halogen, heavy metals and trace elements) composition. The physical and chemical characteristics of the output streams of SRF production are directly related to the type and mass fraction of the input waste stream's components into the output streams. Understanding of the materials flow (i.e. components of input waste) through SRF production facilities can be very useful for SRF manufacturers in order to optimize plant configurations (i.e. flow sheet/arrangements of unit operations) to produce SRF with specific and predictable quality and yield.

There are a number of research studies (Dunnu et al., 2010a; Dunnu et al., 2010b; Montané et al., 2013; Rada and Andreottola, 2012; Kemppainen et al., 2014; Arena and Gregorio, 2014a) which present quality-related data on SRF in terms of its physical and chemical properties. In contrast, there are hardly any published studies available that evaluate and examine in detail the physical and chemical properties of the input and output streams of SRF production. Publications analysing the detailed characterization of the input and output streams produced in the commercial-scale SRF production process in terms of their physical and chemical characteristics are hard to find. There is limited published research (Velis et al., 2011; Velis et al., 2013; Rotter et al., 2004) dealing with certain aspects of the said issue for SRF/RDF.

1.4 Objective of the work

The objective of this research work was to establish the material and energy balance of solid recovered fuel (SRF) production based on an in-depth and detailed analysis and evaluation of the physical and chemical characteristics of waste components and the input and output streams produced in industrial-scale SRF production. Based on the material and energy balance, the mass flow of waste components (paper & cardboard, plastics, wood, textile, rubber), energy content and more importantly polluting and potentially toxic elements (PTEs) from input waste stream into the output streams of SRF production were determined. The polluting and potentially toxic elements included: chlorine (Cl), lead (Pb), cadmium (Cd), arsenic (As) and mercury (Hg). The SRF studied was produced from commercial and industrial waste (C&IW), construction and demolition waste (C&DW) and municipal solid waste (MSW) through mechanical treatment (MT) on full industrial scale. In this research work, the central issues addressed regarding the production of SRF were:

1. The link between SRF quality and the mass flow and share of waste components from the input waste stream into the output streams.
2. The effect of process parameters (i.e. characteristics of input waste feedstock and performance of unit operations used in the process) on the sorting/distribution of waste components into the relevant output streams.
3. The effect of the type of input waste stream on the quality of SRF.

1.5 Thesis organization

This thesis consists of a summary part, and six appended peer-reviewed journal publications, Paper I - VI. The summary of the thesis is discussed in the first six chapters.

Chapter 1 consists of the introduction and relevant background of the subject and the objective of the work. In Chapter 2, the methodology employed to conduct this research work and the experimental set-up is explained and presented. The standard methods of sampling and analysis are described in detail. Chapter 3 summarises the results of mass, energy, material and elemental balances of SRF production from commercial and industrial waste (C&IW). Chapter 4 presents the main results regarding mass, energy, material and elemental balances of SRF production from construction and demolition waste (C&DW). Chapter 5 presents the results of mass, energy, material and elemental balances of SRF production from municipal solid waste (MSW). In Chapter 6, the major results of the work related with material and energy balances, identification of waste components containing polluting and potentially toxic elements (PTEs) and the energy consumed to produce SRF and power available from produced SRF are compared and discussed and the relevant areas of future research are identified. Finally, based on the major findings and results of this research work, conclusions are drawn.

2. Methodology

2.1 Experimental set-up

The research work was based on three industrial-scale experimental campaigns in which solid recovered fuel (SRF) was produced from three different types of waste material through mechanical treatment (MT). The three types of waste material used to produce SRF were:

- Commercial and industrial waste (C&IW)
- Construction and demolition waste (C&DW)
- Municipal solid waste (MSW): Energy waste collected from household

The quantity of C&IW, C&DW and MSW used to produce SRF separately, was 79 tonnes, 74 tonnes and 30 tonnes, respectively. Waste materials were collected from the metropolitan area of the Helsinki region and transported to an MT-based waste sorting plant to produce SRF. Waste collection points were well separated throughout this region. Waste material was collected by trucks/lorries from their respective collection locations.

2.2 Process description

Waste material is treated in the MT-based waste sorting plant to produce SRF. Unit operations/sorting techniques used in the MT plant were: primary shredding, screening (jigging and drum screens), magnetic and eddy current separation, air classification, near-infrared (NIR) sorting units and secondary shredding, as shown in simplified flow diagram Figure 3. Sorting processes (i.e. unit operations) are designed for material sorting based on material properties, e.g. particle size (screening), density/weight (air classification), magnetic properties (magnetic separation) and infrared (IR) spectra (NIR sorting). Mechanical processing of input waste material concentrates suitable waste components into a prepared suitable combustible fraction stream of SRF, and separates out recyclables (metals) and polluting/contaminated and non-combustible waste components into separate small streams. The function of each unit operation/sorting technique used in the MT plant to produce SRF is explained below.

2.2.1 Primary shredding

In primary shredding, the particle size of input waste stream components is reduced to a smaller size (i.e. up to a nominal top size of D_{95} 150 mm). In addition, primary shredding is useful in homogenizing, dealing with large and hard components and opening the closed plastic bags of the input waste stream.

2.2.2 Screening

Screening is the subsequent unit operation used after primary shredding. In screening, jigging and drum screens are used. Waste components having a particle size of D_{95} <15 mm are screened out as fine fraction and components with a large particle size (>300 mm) are separated to be sent back to primary shredding. Waste components having a particle size of between D_{95} 15 mm and 300 mm are treated in further unit operations.

2.2.3 Magnetic and eddy current separation

Components of ferrous and non-ferrous metals are separated out in magnetic and eddy current separators, respectively. Several magnetic and eddy current separating units are used at various locations in the process to recover the maximum amount of metals from the input waste stream for recycling.

2.2.4 Air classification

Light density/weight components (such as paper and cardboard, plastics, textile, foam and wood etc.) are separated in a wind shifter/air classifier and put into the SRF stream. In the wind shifter, air flows in the cross-direction of the falling material and separates lightweight components from heavy and medium-weight components.

2.2.5 Near-infrared (NIR) sorting

Near-infrared (NIR) sensor sorting is based on the near-infrared/specific spectral properties of the components of the waste material. In the NIR sensor, signals are transferred by advanced software to the air nozzles at the end of the conveyor belt and combustible particles are shot over the separating wall into the SRF stream. In the process, the near-infrared (NIR) sensor was set for positive sorting and recognized suitable/combustible components (e.g. paper & cardboard, wood, non-PVC plastics, textile etc.) to put into the SRF stream. Unsuitable/ non-combustible waste components (PVC plastic and other highly chlorinated/contaminated components and inert material) ended up in the reject material stream. The NIR-based sorting technique and principle are explained in detail (Reich, 2005). An automated sorting unit based on NIR technology is shown in Figure 2.

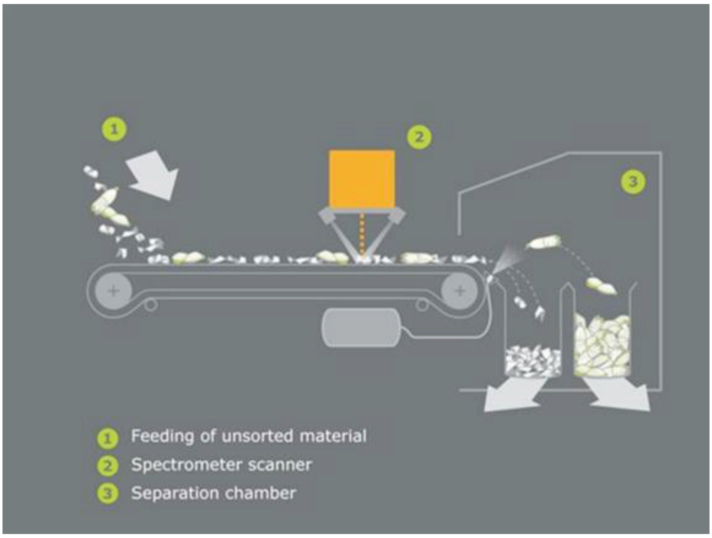


Figure 2: Automated sorting unit based on NIR technology (TITECH/TOMRA)

2.2.6 Secondary shredding

Secondary shredding is the final unit operation in the MT plant in which the particle size of the SRF stream is reduced to < 80 mm. After secondary shredding, SRF is ready to be delivered to customers either as loose material or baled and wrapped.

2.3 Process streams

Based on the unit operations/sorting techniques used in the MT waste sorting plant, the input waste stream was further divided/classified into the various output streams of material, as shown in Figure 3. The input waste streams were C&IW, C&DW and MSW for the three different experimental campaigns. The output streams were:

- Solid recovered fuel (SRF)
- Fine fraction
- Heavy fraction
- Reject material
- Ferrous metal
- Non-ferrous metal

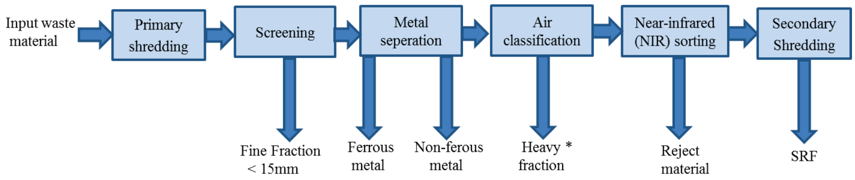


Figure 3: Simplified mechanical treatment process to produce SRF [Paper I]

* In air classification, lightweight components were separated and put in the SRF stream, whereas heavy weight/density components (stones/rock or metallic pieces etc.) were left out as heavy fraction.

2.3.1 Use of the output streams

SRF is a process product and utilized as fuel/co-fuel for energy production in combined heat and power (CHP) gasification and combustion plants; metals (ferrous/non-ferrous) are recycled and streams of reject material, fine fraction and heavy fraction (based on their composition) are utilized partly for energy recovery, environmental construction (landfill construction) and disposal in landfill.

2.4 Sampling methodology

All the process streams (input and output) were sampled from the SRF production plant and further treated for their preparation for laboratory analysis according to CEN standard methods for SRF as mentioned below;

- EN 15442, Solid recovered fuels – methods for sampling.
- EN 15443, Solid recovered fuels – methods for the preparation of the laboratory sample.

2.4.1 Sampling of process streams from SRF production plant

The representativeness of samples of the input and output streams taken from the SRF production plant was ensured by following the CEN standard methods for SRF: EN 15442 Solid recovered fuels – methods for sampling. The methods applied for the sampling of input and output streams from the SRF production plant were:

- Sampling from a static lot
- Manual sampling from a static conveyor belt
- Manual sampling from a drop flow

The sampling method used was based on the operating conditions and practical situation of the SRF production plant and process streams. As per EN

15442, the sampling increment size of process streams was based on their respective top nominal size (D_{95}) and bulk densities, and 24 increments of each stream (except ferrous metal, non-ferrous metal and heavy fraction) were collected. Streams of ferrous metal, non-ferrous metal and heavy fraction were comparatively (i.e. as compared with other streams) homogeneous in their composition, and therefore, it was not necessary to take more than 4 increments for each of these streams. The top nominal size (D_{95}, mm) and sampling quantities of the input and output streams from the SRF production plant are given in Table 2.

Table 2. Sampling quantities of process streams taken from the SRF production plant [Paper I]

Process stream	Top nominal size D_{95} (mm)	Increment size [b] (kg)	Combined sample [c] (kg)
Input waste stream[a]	150	20	480
SRF	75	2.5	60
Reject (D_{95} 85mm)[d]	85	5.0	120
Reject (D_{95} 120mm)[d]	120	10	240
Fine fraction	10	1.0	24
Heavy fraction	150	20	80
Ferrous metal	150	20	80
Non-ferrous metal	150	20	80

[a] Input waste stream represents C&IW, C&DW and MSW used separately in three experimental campaigns. Samples were taken after primary shredding.

[b] Increment size is the portion of material extracted in a single sampling operation.

[c] Combined sample is the sum of 24 increments for the input waste stream, SRF, reject streams and fine fraction, and the sum of four increments for heavy fraction, ferrous metal and non-ferrous metal.

[d] There were two streams of reject material, separated based on their particle size distribution, i.e. reject (D_{95} 85 mm) and reject (D_{95} 120 mm).

The sampling increments of respective streams were combined together to make combined samples of each stream. The top nominal (D_{95}) sizes of process streams were provided by the plant authorities.

2.4.2 Sample preparation of stream's samples for laboratory analysis

The objective was to reduce the original size (mass) of the process stream's combined samples (see Table 2) to a laboratory test sample size (mass) without changing the original composition of the samples. In order to maintain the representativeness of the original samples, the sample preparation for laboratory analysis was performed according to EN 15443: Solid recovered fuels –

methods for the preparation of the laboratory sample. The sample preparation of stream's samples for laboratory analysis was performed in two stages:

- Sample preparation outside the laboratory
- Sample preparation in the laboratory

As per EN 15443, two methods were applied at each stage of sample preparation:

- Particle size reduction
- Sample division (mass reduction)

Sample preparation outside the laboratory:
The particle size reduction of stream samples was done by using a shredder and sieves of various mesh sizes. The top nominal size (D_{95}) of each stream (except metals) was reduced to 30 mm. The fine fraction was not further shredded as it already had a D_{95} of 10 mm. The sample size (mass) at each step after particle size reduction was reduced by the manual increment division method (EN 15442). The metals in each stream were not included in the sample preparation. After sample preparation outside the laboratory, the prepared samples of the input waste stream, SRF, reject (D_{95} 85 mm), reject (D_{95} 120 mm), fine fraction and heavy fraction streams were reduced to 15 kg and that of the fine fraction (D_{95} 10 mm) to 5 kg and sent to the laboratory for further sample preparation and final analysis.

Sample preparation in the laboratory:
In the laboratory, the set-up of apparatus/equipment used for further sample preparation of the stream samples was a cutting mill, crushing mill, grinding mill and riffle divider. This apparatus/equipment was applied in series to reduce the top nominal size (D_{95}) and mass size of samples at each stage of sample preparation. The top nominal size of samples was further reduced by the cutting, crushing and grinding mills from 30 mm to 20 mm, 10 mm and 0.5 mm respectively. The riffle divider was used to reduce the sample size (i.e. sample mass) at every stage after particle size reduction. Through this procedure, the top nominal size (D_{95}) was reduced to 0.5 mm and the mass size to 0.5–5 g of samples of each stream as the final laboratory test analysis sample. The procedure of sample preparation for laboratory analysis of process streams in the laboratory is illustrated in Figure 4. Both reject streams, i.e. reject (D_{95} 85 mm) and reject (D_{95} 120 mm), were combined together into one sample stream as reject material for final laboratory analysis.

Details of the process description, sampling of process streams from the SRF production plant and sample preparation for laboratory analysis are given in the appended Paper I.

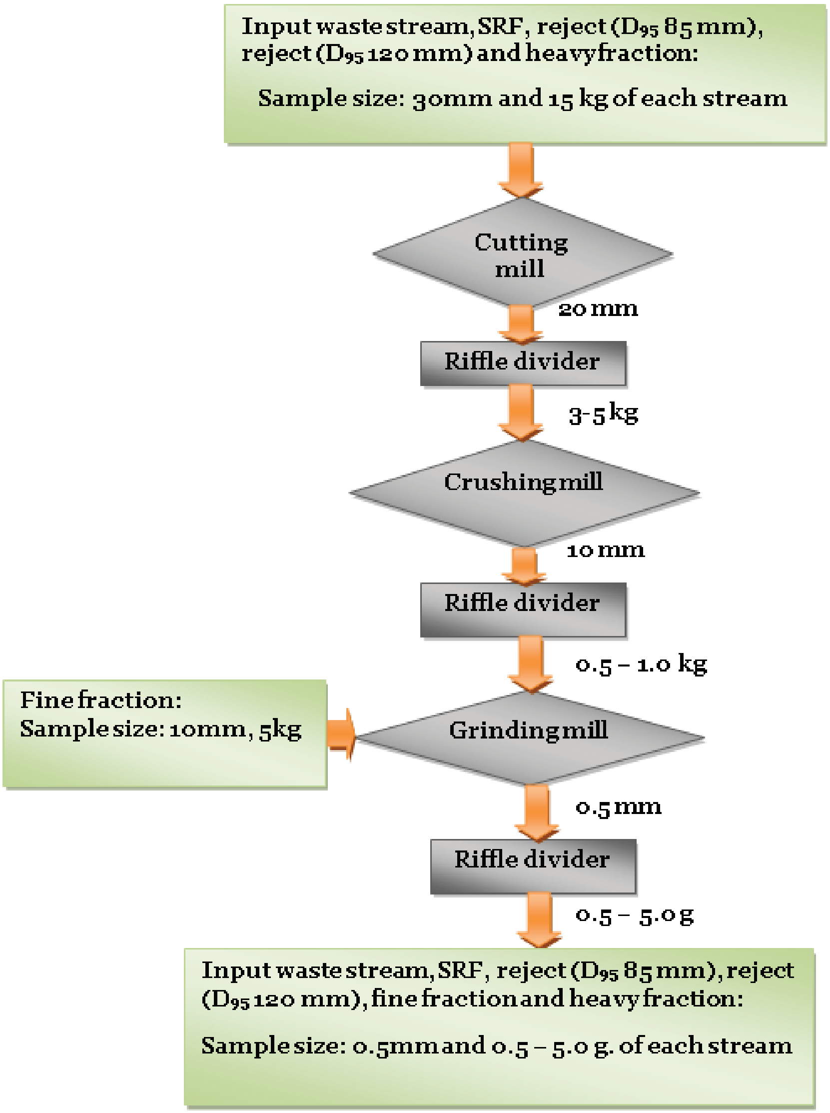


Figure 4: Procedure of sample preparation of process streams in the laboratory [Paper I]

2.5 Sample preparation of waste components

The input waste streams (i.e. C&IW, C&DW and MSW) were manually sorted into their components. Sample preparation of the waste components of the input waste streams was performed by following the same procedure as described for the process streams (described in 2.4.2.). The components of the input waste streams were paper & cardboard, wood, plastic (soft), plastic (hard), textile, rubber, foam and fines.

2.6 Laboratory analysis of process streams and waste components

Prepared samples of input and output streams and the components of input waste streams were comprehensively analysed in the laboratory for their proximate and ultimate analysis and elemental analysis. In the laboratory, standard analysis methods were applied for each sample analysis test. The standard methods used for the laboratory analysis of samples of process streams and waste components are listed in Table 3.

Table 3. Standard methods used for the laboratory analysis of samples of process streams and waste components [Paper II and Paper III]

Analysis parameter	Standard method
Moisture	CEN/TS 15414-2
Ash content (550 °C)	EN 15403
Volatile matter	EN 15402
Biomass content	EN 15440
Heating value	EN 15400
C, H, N, ($O_{\text{calculated}}$)	EN 15407
S	ASTM D 4239 (mod).
Halogen (Cl, Br, F)	SFS-EN ISO 10304-1
Major elements/Heavy metals	SFS-EN ISO11885
Minor elements/Trace elements	SFS-EN ISO 17294-2

Microwave assisted dissolution method was used for SRF samples with different acids/chemicals i.e. hydrogen peroxide (H_2O_2) + nitroxyl (HNO) + hydrofluoric acid (HF) + boric acid (H_3BO_3). Laboratory analysis of major elements, minor elements and halogen was based on elementary analysis: inductively coupled plasma optical emission spectrometry (ICP-OES), inductively coupled plasma mass spectrometry (ICP-MS) respectively.

2.7 Compositional analysis of process streams

Composition of streams means their breakdown by type of material contained (such as paper & cardboard, wood, plastic, textile etc.). The composition of the input and output streams was determined by means of the manual sorting of each stream. Combined samples (see Table 2) of each stream were sorted manually into its components. The waste components were paper & cardboard, plastic (soft), plastic (hard), wood, biowaste (food waste), textile, ferrous metal, non-ferrous metal, foam, rubber, glass and stone/rock.

2.8 Material flow analysis (MFA) approach

The mass flow of polluting and potentially toxic elements (PTEs) from the input waste stream into the output streams was examined and evaluated by means of the elemental balance of the SRF production process. The elemental balance of SRF production was calculated for chlorine (Cl), lead (Pb), cadmium (Cd), arsenic (As) and mercury (Hg). The material flow analysis (MFA) approach was applied to calculate the elemental balance of SRF production. In the process evaluation of waste treatment, MFA is an attractive decision-support tool. MFA is a systematic assessment of the flow of materials within a system defined in space and time. In a waste treatment process, the whereabouts of hazardous chemicals can be determined based on an exact accounting of all substance flows. (Rotter et al., 2004). Methodology for the assessment of waste treatment processes based on the analysis of material flows has been described and published (Rechberger, 2001; Bruner and Rechberger, 2004). The SRF production process evaluated in order to establish the elemental balance by using MFA is shown in Figure 5.

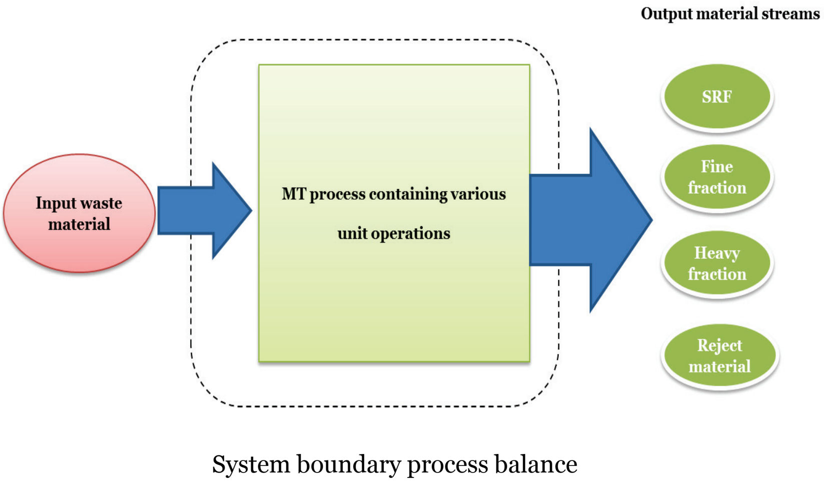


Figure 5: Flow balance of MT process to produce SRF [Paper II]

In the MT-based waste sorting plant, the input waste material was only subjected to mechanical separation and no material transformation (i.e. physical or chemical changes in material) and moreover, the system did not store any material within it. All the input waste material was recovered (with negligible material loss) in the form of output streams. Based on the law of mass conservation, the input mass balance of element(s) was calculated from the sum of its mass in the output streams. The elemental balance was calculated using Eq. (1).

$$X_{input,s} = m_{input} * C_{input,s} = \sum_{i=1}^{k}(m_{pi} * C_{pi,s}) \quad (1)$$

Where X is the load of the element; c is the concentration of the element; m refers to the mass of the stream; pi refers to the output i; (s) refers to the element; and k the number of outputs.

The energy balance of the SRF production process was also calculated based on the MFA approach. The energy flow balance in the process streams of the SRF production process was based on the law of energy conservation; the input energy balance was calculated from the sum of the energy content of the output streams.

The specific load contribution of elements in the components of unsorted waste streams (i.e. input waste streams of C&IW, C&DW and MSW) was determined from the composition of input waste streams and elemental analysis of the waste components. The specific load of an element by a waste component in unsorted/input waste stream was calculated by multiplying the mass fraction of a certain component in the input waste stream with the concentration of the element in the waste component of the input waste stream.

Determination of the uncertainty aspects in sampling (sampling of streams from the SRF production plant) and sub-sampling (sample preparation of process streams for laboratory analysis) required very extensive sampling quantities and was not feasible for this scale of research and therefore, could not be addressed for this work. Determination of the precision of sampling and sub-sampling methods for SRF has been presented in detail (QUOVADIS). The confidence in sampling and measured and calculated values (for elemental analysis of waste components, specific load contribution calculations and elemental balances in the SRF production process) was based on the fact that the sampling of process streams from the SRF production plant and sample preparation for laboratory analysis were performed according to CEN standard methods (EN 15442; EN 15443).

In this work, the mass, material, energy and elemental balances are presented/shown in the form of Sankey diagrams. Sankey diagrams are suitable way to visualize the material and energy balance, in which the width of arrow is proportional to the quantity of flow.

3 Material and energy balance of SRF production from commercial and industrial waste

(Papers I and II)

This chapter presents the material and energy balance of SRF production from commercial and industrial waste (C&IW). In an industrial-scale experimental campaign, SRF was produced from a batch of 79 tonnes of C&IW. Material and energy balances are presented in terms of mass, energy, material (Paper I) and elemental (Paper II) balances of commercial-scale SRF production. Mass balance means the overall mass flow of the input waste stream into the output streams, whereas material balance here refers to the mass balance of the components of the input waste (i.e. paper & cardboard, wood, plastic (soft), plastic (hard), textile and rubber) in the output streams of SRF production. Detailed proximate & ultimate analysis (Paper I) and elemental analysis (Paper II) of the input and output streams and waste components are described. Elemental analysis includes analysis of halogen, heavy metals, major and minor/trace elements. The composition of the input and output streams and the energy consumed to process C&IW in the MT waste sorting plant to produce SRF are also presented (Paper I). Based on the elemental analysis of waste components, the potential sources of polluting and potentially toxic elements (PTEs) were traced and identified (Paper II). The specific elemental load contributed by different waste components was calculated (Paper II) based on the elemental analysis of waste components and composition of C&IW. The whole of this work is presented in appended Papers I and II.

3.1 Proximate & ultimate and elemental analysis of process streams and waste components: SRF produced from C&IW (Paper I & Paper II)

The input and output streams produced in SRF production and the waste components of C&IW were analysed in the laboratory for their proximate & ultimate (Paper I) and elemental analysis (Paper II). The input and output streams included: C&IW (input waste stream), SRF, reject material and fine fraction. Metal (ferrous/non-ferrous) streams were not included in the laboratory analysis. The heavy fraction stream of SRF production was also not included in the laboratory analysis as it contained only 0.4 wt. % of the input material and mainly consisted of inert material (i.e. stones and rocks etc.). The waste components of C&IW included: paper & cardboard, plastic (hard), plastic (soft), textile, wood, rubber, foam and fines. Plastic (hard) and plastic (soft) were separated based on their physical/apparent hardness and softness, for example plastic (soft) mainly included plastic bags etc. and plastic (hard) consisted of hard plastic material (waste components).

The net calorific value (NCV) of SRF produced from C&IW was measured as 18.0 MJ/kg, a.r. and 25.0 MJ/kg, d. This high calorific value of SRF was due to the high mass fraction of plastics in it. The SRF contained 40.5 wt. % of plastics (soft and hard). The NCV of SRF (i.e. 23.56 MJ/kg, d.) was reported in the literature (Vainikka et al., 2011). Plastic components were reported (Rotter et al., 2004; Velis et al., 2011; Nasrullah et al., 2015c) as the major contributor to the calorific value of SRF. The NCV of C&IW and reject material was measured as 13.0 MJ/kg, a.r. and 11.6 MJ/kg, a.r., respectively. C&IW and the reject material stream contained a considerable mass fraction of waste components containing high calorific value, such as plastic, rubber and textile. The ash content (550 °C) of SRF was measured as 12.5 wt. %. Among the SRF production streams, the fine fraction was measured to contain the highest moisture and ash content (550 °C), i.e. 44.5 wt. % and 48.0 wt. %. The high ash content of the fine fraction stream was due to the high mass fraction of inert material (stone/sand/concrete, glass etc.) in it.

Among the components of C&IW, plastic (soft), plastic (hard), foam and textile were measured to have NCV of 37.0 MJ/kg, d. 35.0 MJ/kg, d. 27.3 MJ/kg, d. and 24.8 MJ/kg, d., respectively. The NCV of wood was measured as 18.6 MJ/kg, d. The ash content (550 °C) of rubber material was measured as 23.0 wt. %. Paper & cardboard and textile had a 13.0 wt. % and 10.4 wt. % ash content (550 °C), respectively. Among the waste components, wood was measured to contain the lowest ash content (550 °C), i.e. 1.6 wt. %. The Laboratory analysis results (Paper I) of process streams and components of C&IW taken from the SRF production plant are given in Table 4.

The elemental analysis (Paper II) of the waste components of C&IW and input and output streams are given in Table 5 and Table 6, respectively. In the reject material stream, the chlorine (Cl) content was measured as 1.2 wt. %, which was higher than measured in other output streams. This was due to the high mass fraction of PVC plastic and highly chlorinated rubber material sorted by NIR sorting technology into the reject material stream. The SRF stream was measured to contain 0.6 wt. % of chlorine (Cl). The SRF contained a significant mass fraction of plastic (hard), i.e. 16.5 wt. %. In plastic (hard), the chlorine content was measured as 3.0 wt. %. The chlorine content of SRF could be related to the high contribution of plastic (hard) it contained. Among the waste components, rubber and plastic (hard) were measured to contain 8.0 wt. % and 3.0 wt. % chlorine (Cl), respectively, which was higher than measured in other components. Among waste components, a high chlorine content has been reported (Rotter et al., 2004; Roos and Peters 2007; Velis et al., 2013; Nasrullah et al., 2015b; Nasrullah et al., 2015c) in plastic, rubber, leather and shoes. The reject material was measured to contain 0.3 wt. % of bromine (Br), which was considerably higher than that measured in other output streams. Among the waste components, textile was measured to contain a far higher bromine content than other components. Textile was measured to contain 0.06 wt. % of bromine (Br). It was found that, in textile especially, the synthetic textile component contained higher bromine content than normal textile (fibrous-based). The antimony (Sb) content in the reject material was measured as high as 1160 mg/kg. Textile was also measured to contain a significantly higher antimony content than other waste components, i.e. 360 mg/kg. The reject stream contained a sizeable mass fraction of textile, i.e. 9.2 wt. %, which was higher than in other process streams, causing its higher bromine and antimony content. Flame-retardant textiles were reported (Vainikka et al., 2011; Vainikka and Hupa, 2012; Wua et al., 2014) to be one of the main sources of bromine (Br) in waste components. The fine fraction and reject material were measured to contain 9.8 mg/kg and 7.0 mg/kg of arsenic (As) content, respectively. Among the waste components, textile was measured to have a comparatively higher arsenic (As) content than the others. Rubber material clearly had a higher cadmium (Cd) content, i.e. 11.0 mg/kg, than the other components. Lead (Pb) was comparatively measured to be homogeneously distributed among the reject material, fine fraction and SRF. Plastic (hard) was measured to contain 400 mg/kg of lead (Pb), which was higher than the other waste components. A higher mercury (Hg) content was measured in the fine fraction compared with other output streams, i.e. 0.4 mg/kg. Among the waste components, textile and foam were measured to contain 0.2 mg/kg of mercury (Hg) each.

Among the output streams of SRF production, the reject material was measured (Paper II) to contain a higher concentration of polluting and PTEs, especially chlorine (Cl), bromine (Br), antimony (Sb) and cadmium (Cd) as compared with other output streams (Table 6). After the reject material, the fine fraction was found to be the second most polluting stream, especially as it was measured to contain a higher concentration of mercury (Hg), lead (Pb) and arsenic (As) than measured in other output streams (Table 6). The fine fraction was also measured to have a higher moisture and ash content than other streams (Table 4). Among the components of C&IW (input waste stream), rubber, plastic (hard) and textile (to a certain extent, especially synthetic type textile) were identified (Table 5) as potential sources of polluting and PTEs, especially in terms of chlorine (Cl), arsenic (As), cadmium (Cd) and lead (Pb).

Table 4: Laboratory analysis results of process streams and components of C&IW taken from the SRF production plant (mean value of three laboratory test sub-samples) (Paper I)

Parameters	Moist. cont.	Ash cont. 550°C	C	H	N	S	$O_{calc.}$	NCV[a]	GCV[b]	NCV[a]
stream	wt. %	wt. %	wt.%	wt. %	wt. %	wt. %	wt. %	MJ/kg (a.r.)[c]	MJ/kg (d.)[d]	MJ/kg (d.)[d]
C&IW	26.5	16.6	48.0	7.0	0.6	0.2	18.0	13.0	19.8	18.5
SRF	25.0	12.5	57.4	8.0	0.5	0.3	17.8	18.0	26.6	25.0
Reject	26.0	23.0	41.0	5.8	1.0	0.3	20.8	11.6	18.8	16.6
Fine fraction	44.5	48.0	29.6	4.0	1.2	0.8	16.0	5.5	12.6	12.0
Components of C&IW										
Paper & card	n.a.	13.0	42.5	5.6	0.4	0.1	38.0	n.a.	17.3	16.0
Plastic (soft)[e]	n.a.	10.3	74.6	12.0	0.3	0.2	2.3	n.a.	39.5	37.0
Plastic (hard)[e]	n.a.	6.0	74.4	11.4	0.3	0.1	5.0	n.a.	37.4	35.0
Textile	n.a.	10.4	57.4	7.6	1.8	0.24	21.3	n.a.	26.5	24.8
Wood	n.a.	1.6	49.0	6.2	0.8	<0.02	42.2	n.a.	20.0	18.6
Rubber	n.a.	23.0	48.0	5.2	1.0	0.5	14.3	n.a.	21.0	20.0
Foam	n.a.	5.0	62.5	8.4	4.0	0.1	19.8	n.a.	29.0	27.3
Fines	n.a.	54.4	26.8	3.5	1.3	1.0	22.6	n.a.	10.6	9.8

[a] NCV: net calorific value

[b] GCV; gross calorific value

[c] (a.r.): as-received basis of material

[d] (d.): dry basis of material

[e] Plastic (soft) and plastic (hard); separated on the basis of their physical hardness

n.a.: not available

Table 5: Elemental analysis of components of commercial and industrial waste (mean value of three laboratory test sub-samples, dry basis of material) (Paper II)

#	Element	Unit	Paper & cardboard	Plastic (hard)	Plastic (soft)	Textile	Rubber	Foam	Wood	Fines
1	Cl	wt %, d	0.2	3.0	0.14	1.0	8.0	0.2	0.075	0.4
2	Br	wt %, d	<0.001	0.002	<0.001	0.06	<0.001	0.002	<0.001	0.002
3	F	wt %, d	0.002	0.002	0.002	0.003	0.002	0.002	<0.001	0.007
4	S	wt %, d	0.1	0.08	0.08	0.2	0.5	0.1	<0.02	1.0
5	Na	mg/kg, d	2300	820	2800	2300	1100	1000	780	26400
6	K	mg/kg, d	1100	570	2000	1700	1200	1100	990	9700
7	Ca	mg/kg, d	39500	16200	14800	21100	75400	14200	2500	66800
8	Mg	mg/kg, d	1700	2200	1400	860	11300	860	280	6000
9	P	mg/kg, d	230	240	550	330	420	290	120	1500
10	Al	mg/kg, d	11400	3300	4600	2600	2900	1500	510	23200
11	Si	mg/kg, d	9000	6100	16300	9400	17500	5300	1700	57100
12	Fe	mg/kg, d	1100	1000	8000	1700	1900	1500	690	19400
13	Ti	mg/kg, d	920	3500	4000	1000	4400	740	330	10200
14	Cr	mg/kg, d	12	80	30	360	1300	20	7.3	270
15	Cu	mg/kg, d	20	3.6	80	21	1400	16	5.0	500
16	Mn	mg/kg, d	48	60	76	120	50	32	75	260
17	Ni	mg/kg, d	6.0	28	15	12	20	7.7	5.7	150
18	Zn	mg/kg, d	88	370	420	150	5500	260	80	1400
19	Sb	mg/kg, d	4.4	84	12	360	30	40	1.2	23
20	As	mg/kg, d	<0.5	0.6	1.0	2.0	1.2	1.6	<0.5	5.5
21	Ba	mg/kg, d	55	240	280	120	1300	420	31.0	1300
22	Cd	mg/kg, d	0.1	2.7	0.2	0.2	11.0	0.1	0.16	1.3
23	Co	mg/kg, d	2.0	3.3	180	31.0	2.0	2.0	0.8	12.0
24	Pb	mg/kg, d	9.5	400	76.0	17.0	250	16.0	3.0	320
25	Mo	mg/kg, d	0.7	3.7	3.0	3.5	2.2	4.2	<0.5	1300
26	Se	mg/kg, d	<0.5	0.5	<0.5	0.5	0.6	0.5	<0.5	3.0
27	Tl	mg/kg, d	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
28	Sn	mg/kg, d	2.0	13.0	9.8	5.3	100	260	0.6	36
29	V	mg/kg, d	3.7	1.8	4.2	2.7	17.0	2.6	0.7	18.0
30	Hg	mg/kg, d	<0.05	0.05	0.4	0.2	0.08	0.2	<0.05	0.3

Table 6: Elemental analysis of input and output streams produced in SRF production: SRF produced from commercial and industrial waste (mean value of three laboratory test sub-samples, dry basis of material) (Paper II)

#	Element	Unit	Input waste stream	Reject material stream	Fine fraction stream	SRF stream
1	Cl	wt %, d	0.6	1.2	0.4	0.6
2	F	wt %, d	0.007	0.008	0.01	0.01
3	Br	wt %, d	0.005	0.3	0.006	0.003
4	S	wt %, d	0.2	0.3	0.8	0.3
5	Na	mg/kg, d	2990	4450	23300	3460
6	K	mg/kg, d	2150	2900	8800	2175
7	Ca	mg/kg, d	18530	39540	57000	36260
8	Mg	mg/kg, d	1590	2420	5200	1480
9	P	mg/kg, d	870	775	1600	960
10	Al	mg/kg, d	7300	14230	19900	8200
11	Si	mg/kg, d	22180	25020	58600	18870
12	Fe	mg/kg, d	4400	4160	12000	4840
13	Ti	mg/kg, d	3090	2130	5700	3160
14	Cr	mg/kg, d	290	80	190	50
15	Cu	mg/kg, d	5800	1015	330	375
16	Mn	mg/kg, d	110	100	210	80
17	Ni	mg/kg, d	20	45	95	20
18	Zn	mg/kg, d	4120	540	1000	335
19	Sb	mg/kg, d	7.2	1160	30	50
20	As	mg/kg, d	5.0	7.0	9.8	1.8
21	Ba	mg/kg, d	290	415	880	290
22	Cd	mg/kg, d	1.2	1.5	1.0	0.6
23	Co	mg/kg, d	2.4	4.8	10	3.6
24	Pb	mg/kg, d	90	150	235	120
25	Mo	mg/kg, d	3.0	4.3	10	3.6
26	Se	mg/kg, d	0.5	<0.5	1.7	0.5
27	Tl	mg/kg, d	<0.5	<0.5	<0.5	<0.5
28	Sn	mg/kg, d	8.8	34	25	18.8
29	V	mg/kg, d	6.0	7.7	16	5.3
30	Hg	mg/kg, d	0.1	0.2	0.4	0.1

3.2 Mass, energy and material balances of SRF production: SRF produced from C&IW (Paper I)

The mass balance of the SRF production process was established for a batch of 79 tonnes of C&IW fed to MT waste sorting plant to produce SRF. Based on the unit operations/sorting techniques used in the MT plant, the input waste stream (C&IW) was divided into various output streams: SRF, fine fraction, heavy fraction, reject material, ferrous metal and non-ferrous metal. All the output streams were weighed. All the input waste material was recovered in the form of output streams with a negligible amount of difference. Of the total input C&IW material enetring the process (by weight) , 62 % of the material was recovered in the form of SRF, 5 % in the form of metals, 21 % was separated as as reject material, 11.6 % as fine fractionand 0.4 % as heavy fraction. The mass balance of SRF production from C&IW is shown in Figure 6.

The energy flow balance from the input waste stream (C&IW) into the output streams of SRF production was calculated based on the material flow analysis (MFA) approach (described in Section 2.8). By applying the law of energy conservation, the input energy balance was calculated from the sum of the energy content of the output streams. The energy content of the output streams was calculated by multiplying their heating values (NCV, MJ/kg) (given in Table 4) by their respective total mass (from the mass balance of SRF production as shown in Figure 6) for both the wet and dry basis of material. The energy content of the heavy fraction stream was calculated from its composition and the heating values of waste components it contained (given in Table 4). The difference between the measured and calculated values of the input energy content is calculated as an error value. In the SRF production, energy recovered in the form of SRF was 75% and 78% of the total input energy for wet and dry basis of material respectively. The energy connected with the metal streams (ferrous metal and nonferrous metal) was due to a very minor amount of combustibles (such as paper & cardboard, plastic, foam and wood) in these streams not due to the metals, as the energy content of metals was considered to be zero (Biffaward, 2003). The energy content of the reject material and fine fraction was a result of the considerable mass fraction of components such as plastics, rubber, paper and cardboard and wood (to a smaller extent) in these streams. The energy flow balance in the process streams of SRF production from C&IW on wet and dry basis is shown in Figure 7.

The energy consumed for a process batch of 79 tonnes of C&IW at the MT waste sorting plant to produce SRF was calculated in terms of in-plant operations and out-plant operations. In-plant operations included unit operations/sorting techniques used in the MT plant such as shredding, screening, magnetic/eddy current separation, air classifiers, NIR sorting units, conveyor belts, a dust extraction system and material handling vehicles (wheel loaders and excavators). Out-plant operations included the logistical means involved in collecting C&IW from its collection points and delivering it to the MT plant; out-plant operations also included the transportation for delivering the output streams (SRF, metals, reject material, fine and heavy fraction) to the customers' premises. The energy consumed per unit tonne of feed (input waste stream of C&IW) was calculated (Paper I) as 60 kWh and 130 kWh for in-plant operations and out-plant operations respectively.

The material balance of SRF production included the mass balance of waste components from the input waste stream into the various output streams. Waste components for which material balances were calculated were paper & cardboard, wood, plastic (soft), plastic (hard), textile and rubber. In order to optimize the plant configuration to produce SRF with predictable and specified quality, the flow of waste components (paper, plastics, wood, etc.) through an SRF production facility needs to be understood (Velis et al., 2013). The calculation of the material balance (Paper I) was based on the composition of the input and output streams (see Section 3.3.) and the overall mass balance of SRF production (see Figure 6).

The material balance showed (Paper I) that the recovery of plastic (soft) from input waste into the SRF stream was on the high side. Of the total input plastic (soft), 88 wt. % was recovered in the SRF. On the other hand, the recovery of paper & cardboard and wood components was not as high as that of plastic (soft). Of the total paper & cardboard and wood entering the process, 72 wt. % and 60 wt. %, respectively, were recovered in the SRF. A sizeable mass fraction of paper & cardboard and wood was found in the reject material stream, which was supposed to be in the SRF stream. It was found that the majority of the paper & cardboard and wood components found in the reject material were highly moist (> 25 wt. %), large in particle size (> 200 mm) or irregular in shape (paper in rolled/bundled form). Primary shredding of input waste material could have caused the cross-contamination of moisture content to paper and cardboard from other components with a high moisture content. The recovery of textile components was also comparatively on the low side. Of the total textile entering the process, 58 wt. % was recovered in the SRF and 21 wt. % was found in the reject material. As described in the elemental analysis of waste components (Table 5), textile was measured to contain 1.0 wt. % of chlorine (Cl). Textile was also measured to contain a much higher concentration of bromine (Br) and antimony (Sb) as compared with other waste components. Some textile components in the reject material were found to have a high moisture (> 25 wt. %) content and to be larger in particle size (> 200 mm). Of the total input plastic (hard), 70 wt. % was recovered in the SRF and 20 wt. % was found in the reject material. A major fraction of plastic (hard) found in the reject material contained PVC plastics (highly chlorinated). In the case of rubber, the majority was separated into the reject material. Of the total rubber entering the process, 56 wt. % was found in the reject material. Rubber material found in the reject material was measured to have a high chlorine content. As described in the elemental analysis of C&IW components, among the waste components rubber was measured to have the highest chlorine content, i.e. 8.0 wt. % (Table 5).

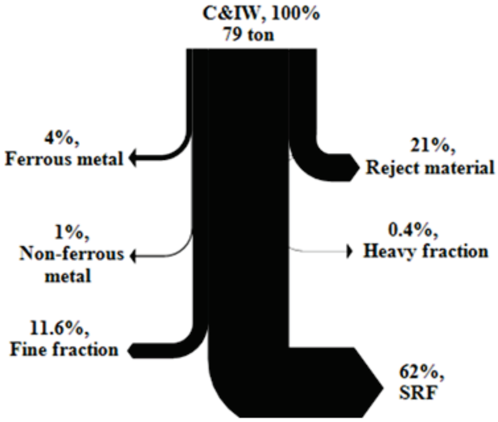


Figure 6: Mass balance of SRF production from C&IW (basis of material) (Paper I)

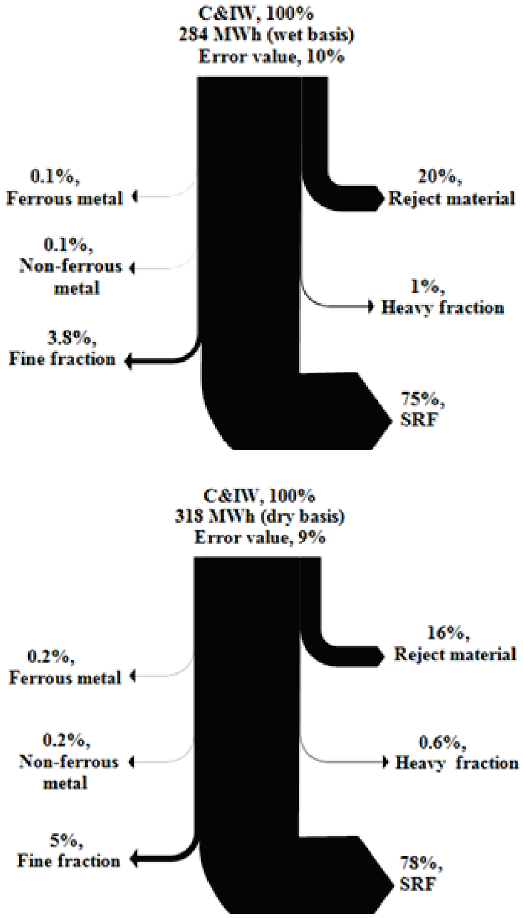


Figure 7: Energy flow balance in process streams of SRF production from C&IW (Paper I)

The use of near-infrared (NIR) technology in the SRF production process proved very helpful in separating waste components such as PVC plastic, rubber and to some extent textiles (especially the synthetic type) containing polluting elements (especially chlorine) from the input waste stream into the reject material. In the newly built mechanical biological treatment (MBT) plants, the use of NIR technology has reduced the total chlorine content of SRF by removing highly chlorinated plastic components (Schirmer et al., 2007). The material balance of paper & cardboard, wood, plastic (soft), plastic (hard), textile and rubber for SRF production from C&IW is presented in Paper I, which describes and explains the recovery of input waste components into SRF.

3.3 Composition of input and output streams

The composition of streams means their breakdown by type of material contained (such as paper & cardboard, wood, plastic, textile etc.). The composition of the input and output streams was determined by manual sorting of their respective combined samples (Table 2).

The C&IW (input waste stream) mainly contained paper & cardboard and plastics. The C&IW contained 31 wt. % of paper & cardboard and 31.6 wt. % of plastics (hard and soft). In the SRF produced from C&IW, the mass fraction of paper & cardboard and plastics was further enriched. The SRF contained 35.6 wt. % of paper & cardboard and 40.5 wt. % of plastics (hard and soft) and 8.5 wt. % of textile as major components. Paper and cardboard has been reported (Velis et al., 2011; Nasrullah et al., 2015a) as a dominant fraction of SRF. In this SRF, the mass fraction of plastic (soft) was higher than that of plastic (hard). In the reject material, inert material (stone/rock and glass) and fines were the major fractions, i.e. 28.5 wt. % and 17.0 wt. %, respectively. There was also a significant mass fraction of plastic (hard) and rubber in the reject material, i.e. 14.0 wt. % and 6.8 wt. %, respectively. In the reject material, the plastic (hard) was mainly PVC plastic and the rubber was highly chlorinated. The heavy fraction contained mainly stone/rock (heavy particles). The composition of input and output streams produced in SRF production from C&IW is presented and discussed in Paper I.

The energy-based composition of SRF was calculated (Paper I) based on the SRF composition (on mass basis) and net calorific values of its components (given in Table 4). It was calculated by multiplying the mass fraction of components of SRF by their respective net calorific values. The major energy content of SRF was found to be contained in plastic (soft), plastic (hard) and paper & cardboard. Plastics (soft and hard) and paper & cardboard in the SRF stream accounted for 59.6% and 23.1% of the total energy content of SRF respectively. The energy-based composition of SRF produced from C&IW is shown in Figure 8.

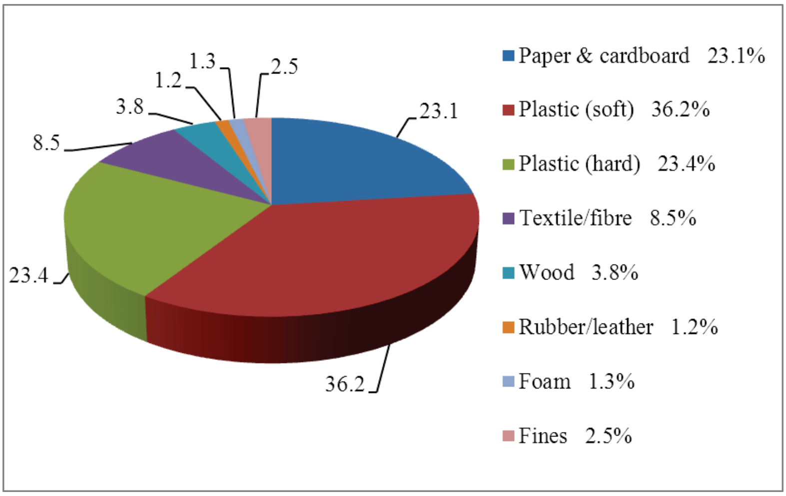


Figure 8: Energy-based composition of SRF produced from C&IW [Paper I]

3.4 Elemental balance of SRF production from C&IW

The elemental balance of SRF production was calculated [Paper II] for polluting and PTEs; chlorine (Cl), arsenic (As), cadmium (Cd), lead (Pb) and mercury (Hg). The mass flow of polluting and PTEs from the input waste stream into the output streams was examined and evaluated by means of an elemental balance of SRF production. The elemental balance of SRF production from C&IW is shown in Figure 9.

In the elemental balance of SRF production, of the chlorine (Cl) and lead (Pb) content entering the process, 60 wt. % and 58 wt. % respectively were found in the SRF stream and 40 wt. % and 42 wt. % respectively were separated in other output streams. Of the cadmium (Cd) content entering the process, 54 wt. % was separated in other output streams and 46 wt. % was found in the SRF. Of the mercury (Hg) content entering the process, 55 wt. % was separated in other output streams, while 45 wt. %, was found in the SRF. In the case of arsenic (As), 68 wt. % of the content entering the process was separated in other output streams and 32 wt. % was found in the SRF (Figure 9). Here, the term ‘other output streams’ refers to those besides SRF, i.e. reject material, fine fraction and heavy fraction.

Among the unit operations used in the MT process, the air classifier and NIR sorting unit were the most effective in determining the quality of SRF. The major distribution of combustible components (paper & cardboard, wood, non-PVC plastics, suitable textile and other components) and non-suitable components (PVC plastic, highly chlorinated rubber and waste components containing high concentration of PTEs) into SRF and reject material was performed by the air classifier and NIR sorting units.

As described earlier, the reject material stream was found to contain a significant mass fraction of combustible components (especially paper & cardboard and wood and to a certain extent textile), which were supposed to be in the SRF. Waste components (paper & cardboard and wood and to a certain extent textile) found in the reject material were either large in particle size (> 200 mm), highly moist (> 25 wt. %) or irregular in shape (for example paper & cardboard and textile in bundled form). For these combustible components, their heavy weight/density (due to high moisture, bundled form etc.) and larger particle size could be the reason for not being sorted properly by the air classifier and NIR sorting unit into the SRF stream. As shown in the elemental analysis of waste components (Table 5), paper & cardboard and wood contained the least amount of polluting and PTEs as compared with other waste components. Therefore, the recovery of paper & cardboard and wood (found in the reject material) into the SRF stream could have effectively reduced the polluting elements and PTEs content of the SRF.

On the other hand, rubber, plastic (hard) and textile (to a certain extent, especially synthetic textile) were measured to contain the highest concentration of polluting and PTEs among the waste components of C&IW (Table 5). During the operation of the air classifier, some lightweight components of rubber, plastic (hard) and textile (especially synthetic type) containing a high concentration of polluting and PTEs could have been sorted/separated and put into the SRF stream. The sorting of these components into the SRF stream could have caused a higher mass flow of chlorine (Cl), cadmium (Cd), lead (Pb) and mercury (Hg) into the SRF stream as compared with the other output streams (Figure 9). Making one pass/check of NIR sorting (with negative sorting) to the air-classified fraction before the components entered the SRF stream could have prevented certain undesired components of rubber, plastic (hard) and textile (to a certain extent, especially synthetic textile) from entering the SRF stream and reduced the concentration of polluting and PTEs in the SRF.

The flow rate of the input waste stream was also observed as a very important process parameter, which might have affected (negatively) the proper sorting of incoming waste components into the relevant output streams. Sudden/quick/non-steady peaks of material passing from the unit operations might have affected (in a negative way) the operating performance of the unit operations (especially the air classifier and NIR sorting unit) and certain desirable components (especially paper & cardboard and wood) missed separation/sorting (by the air classifier or/and NIR sorting unit) into the SRF and ended up in the reject material. It is important to balance the mass flows of the plant by steady feeding of input waste at the start of the process and adjusting processes so that the mass flows of material pass from the processes (unit operations) steadily and as per the designed capacities of the equipment. In this way, the issue of too many or sudden peaks of material coming to any of the sorting processes could be addressed. Regular maintenance checks/inspection are also vital (e.g. keeping the air nozzles of the NIR units clean) to make sure that the machines are functioning properly and that the set-ups are correct.

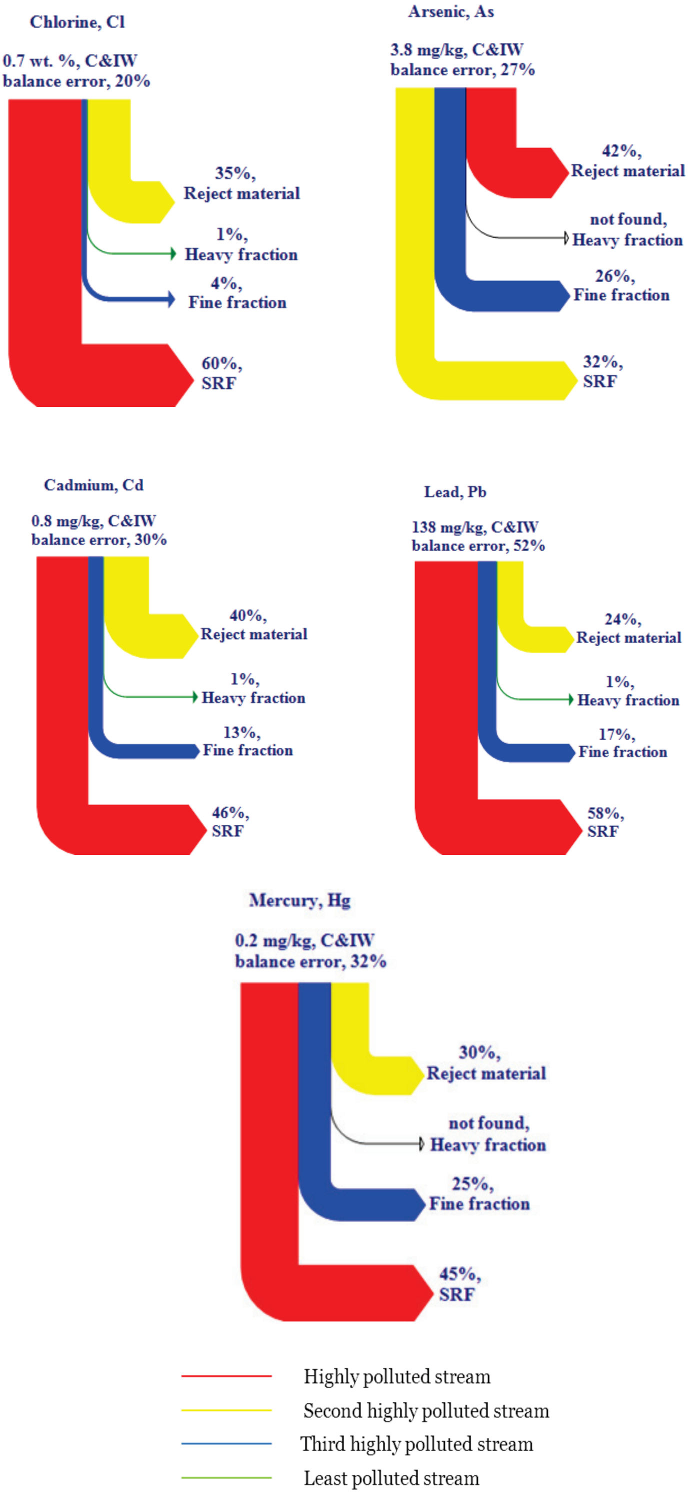


Figure 9: Elemental balance of SRF production from commercial and industrial waste [Paper II]

The specific load contribution of polluting elements and PTEs by waste component in unsorted C&IW was calculated [Paper II] based on the composition of the C&IW and elemental analysis of the waste components. To calculate the specific load of an element contributed by waste component in unsorted C&IW (i.e. input waste stream), the mass fraction of that component in C&IW was multiplied by the concentration of the element in that component. The highest load of chlorine in unsorted C&IW was found to be contributed by plastic (hard) components. Plastic (hard) was also found to carry a higher load of lead and cadmium in C&IW as compared with other waste components.

Of the total load of chlorine, cadmium and lead in unsorted C&IW, 51%, 47% and 59%, respectively, were calculated to be carried by plastic (hard) components (Paper II). Rubber material was found to carry a 20% load of chlorine (Cl) and about 35 % of cadmium (Cd) in unsorted C&IW. Textile components were calculated to carry a considerably higher load of bromine (Br) and antimony (Sb) than other waste components, i.e. 84.6% and 64.3%, respectively, of the total load in unsorted C&IW. A higher load of arsenic (As) was carried by fines, i.e. 29% of its total load in C&IW as compared with the other waste components. The specific elemental load contribution by waste components in unsorted C&IW is shown and discussed in Paper II.

Major findings

- Of the C&IW entering the process, 62 wt. % was recovered in the form of SRF and 5 wt. % as metals (ferrous and non-ferrous). The energy recovered in the form of SRF was 75 % (on wet basis) and 78 % (on dry basis) of the total energy content of C&IW entering the process. The energy consumed to process C&IW in the MT plant to produce SRF was calculated in the forms of in-plant and out-plant operations. The energy consumed per unit tonne of feed for in-plant operations and out-plant operations was calculated as 60 kWh and 130 kWh, respectively.
- In the composition of C&IW, paper & cardboard and plastics (soft and hard) were the dominant waste components, with 31 wt. % and 31.5 wt. %, respectively. The SRF produced from C&IW was further enriched with paper & cardboard and plastics (soft and hard) containing 35.6 wt. % and 40.5 wt. %, respectively. In the SRF, the mass fraction of plastic (soft) was higher than that of plastic (hard). The reject material separated in the process mainly consisted of highly chlorinated rubber, PVC plastic and inert material (stone/rock, glass and a very small fraction of metals).
- In the elemental balance of SRF production, of the chlorine (Cl) and lead (Pb) content entering the process in the feed, 40 wt. % and 42 wt. % respectively were separated/sorted into other output streams. In the case of cadmium (Cd), 54 wt. % of the content entering the process was separated into other output streams. As for mercury (Hg), 55 wt. % of the content entering the process was separated into other output streams. In the case of arsenic (As), 68 wt. % of the content was sepa-

rated into other output streams. 'Other output streams' here refer to those besides SRF, i.e. reject material, fine fraction and heavy fraction.

- Among the components of C&IW, rubber and plastic (hard) were measured to contain 8.0 wt. % and 3.0 wt. % (dry basis) respectively of chlorine (Cl), which was higher than that measured in other components. Plastic (hard) was also measured to contain a higher content of lead (Pb), i.e. 400 mg/kg, d. than the other waste components. In rubber, a higher cadmium (Cd) content was measured than that in other components of C&IW. Paper and cardboard, wood, and foam were among the components containing the lowest amount of polluting elements and PTEs.
- Recovery of combustible components (especially paper & cardboard and wood) from the reject material stream into the SRF stream could have further enhance the yield of SRF and effectively reduce the content of polluting elements and PTEs in the SRF.

4 Material and energy balance of SRF production from construction and demolition waste

(Papers III and IV)

This chapter deals with the material and energy balance of SRF production from construction and demolition waste (C&DW). The SRF was produced on industrial scale from a batch of 74 tonnes of C&DW through mechanical treatment (MT). The results presented here comprised the proximate & ultimate analysis (Paper III) and elemental analysis (Paper IV) of the input and output streams in SRF production, the elemental analysis (Paper IV) of the components of C&DW, the composition of streams and the mass, energy, material (Paper III) and elemental balances (Paper IV) of SRF production. The mass flow of polluting elements and PTEs was calculated (Paper IV) in terms of the elemental balance of SRF production. The potential source of polluting elements and PTEs in C&DW were identified (Paper IV). The whole of this work is presented in appended Papers III and IV.

4.1 Proximate & ultimate and elemental analysis of process streams and waste components: SRF produced from C&D waste (Paper III and Paper IV)

The proximate & ultimate (Paper III) and elemental analysis (Paper IV) of the input and output streams in SRF production from C&DW were performed in the laboratory. In the elemental analysis (Paper IV), the concentration of halogen, heavy metals, and major and minor/trace elements was measured. Here, the input stream was the C&DW used to produce SRF, and the output streams included SRF, reject material, fine fraction and heavy fraction. Metals in each stream were excluded from laboratory analysis.

The results of the laboratory analysis of the streams (input and output) produced in SRF production from construction and demolition waste are given in Table 7. The SRF produced from C&DW was measured to contain an NCV of 18.0 MJ/kg, a.r. basis and 20.0 MJ/kg, d. basis. The dominant energy fraction of SRF was due to the high mass fraction of wood, plastics and paper & cardboard it contained. The SRF was measured to have 66.7 wt. % of bio carbon from the total carbon content. The majority of the bio carbon in the SRF was due to the wood fraction it contained. The moisture content and ash content (550 °C) of SRF were measured as 16.5 wt. % and 9.0 wt. %, respectively. C&D waste (input waste stream) was measured to have an NCV of 9.8 MJ/kg, a.r. and 11.0 MJ/kg, d. The ash content (550 °C) of C&D waste was measured as high as 46.8 wt. %, which was due to the high mass fraction of building material (inert material) in it. In the composition of C&D waste, the mass fraction of building material and fines (fines mainly contained fine particles of building material as well) was 14.2 wt. % and 16.6 wt. %, respectively. The high ash content (550 °C) of the fine fraction and heavy fraction streams, i.e. 78.8 wt. %

and 65.6 wt. %, was also due to the very high mass fraction of building material (inert material) in these streams.

Table 7: Laboratory analysis results of process streams in SRF production from construction and demolition waste (mean value of three laboratory test sub-samples) (Paper III)

Process Streams	Moist cont. wt%	Ash 550°C wt%	Volat. matter wt%	Bio[a] cont. wt%	C (d.) wt%	H (d.) wt%	N (d.) wt%	S (d.) wt%	$O_{calc.}$ (d.) wt%	NCV (a.r.)[d] MJ/kg	NCV (d.)[e] MJ/kg
C&DW	14.0	46.8	n.a.	n.a.	30.0	4.0	0.5	0.7	17	9.8	11.0
SRF	16.5	9.0	76.6	66.7	50.0	6.4	1.0	0.3	31.6	18.0	20.0
Reject	12.0	47.2	n.a.	n.a.	31.2	3.8	0.6	0.7	16.2	10.0	12.0
Fine f.[b]	23.6	78.8	n.a.	n.a.	12.0	1.3	0.4	2.8	4.8	2.5	4.0
Heavy f[c]	10.4	65.6	n.a.	n.a.	20.0	2.6	0.5	0.3	13.2	6.5	7.6

a Bio. Cont: biomass content in % bio carbon
b Fine f: Fine fraction stream
c Heavy f: Heavy fraction stream
d (a.r.): as-received basis of material
e (d.): dry basis of material

In the elemental analysis of the components of C&D waste, rubber, plastic (hard) and textile (especially synthetic type textile components) were found as potential sources of chlorine (Cl). Rubber, plastic (hard) and textile were measured to contain 7.6 wt. %, 7.0 wt. % and 3.8 wt. % of chlorine (Cl), respectively. The cadmium (Cd) content measured in rubber was also higher than that measured in other waste components. Among the waste components, foam material was measured to contain a higher bromine (Br) concentration, i.e. 0.013 wt. %. Foam material mainly comprised foam used for insulation in buildings and to some extent packaging type foam. Textile components were found to have higher arsenic (As) concentration, i.e. 12.0 mg/kg than that measured in other waste components. The lead (Pb) content measured in plastic (hard) was 880 mg/kg, which was higher than that measured in other waste components. After plastic (hard), textile was measured to contain 450 mg/kg of lead (Pb). Plastic (soft) and textile were measured to contain 0.2 mg/kg of mercury (Hg) each. The elemental analysis of components of C&D waste is given in Table 8.

Among the components of C&D waste (input waste stream), rubber, plastic (hard) and textile (especially synthetic type textile components) were identified as the potential sources of polluting elements and PTEs. Conversely, paper & cardboard, wood, plastic (soft) and foam were found to contain the least amount of polluting elements and PTEs.

An elemental analysis of the input and output streams of SRF production from C&D waste was performed (Paper IV). The reject material stream was measured to contain higher chlorine (Cl) content, i.e. 2.2 wt. % (Table 9). This higher chlorine concentration was due to the high mass fraction of rubber and highly chlorinated plastic (PVC plastic) in the reject material stream. In the composition of reject material, the mass fraction of rubber and plastic (hard) was 15.0 wt. % and 7.4 wt. %, respectively. Apart from rubber and plastic (hard), the mass fraction of textile in the reject material was also considerable, i.e. 3.4 wt. %. Rubber, plastic (hard) and textile were the components measured to contain higher chlorine (Table 8) as compared with other components. Chlorine content measured in the SRF was 0.4 wt. % (Table 9). In the SRF high mass fraction of wood and paper & cardboard effectively reduced the overall chlorine concentration in it. In the composition of SRF, mass fraction of wood and paper & cardboard was 38 % and 22% respectively. Among the components of C&D waste, wood, plastic (soft) and paper & cardboard were measured to contain the lowest chlorine content.

Table 8: Elemental analysis of the components of construction and demolition waste (mean value of three laboratory test sub-samples, dry basis of material) (Paper IV)

#	Element	Unit	Paper & cardboard	Plastic (hard)	Plastic (soft)	Textile	Rubber	Foam	Wood
1	Cl	wt %, d	0.3	7.0	0.18	3.8	7.6	0.32	0.037
2	F	wt %, d	0.004	0.013	0.006	0.006	0.006	0.003	0.001
3	Br	wt %, d	0.001	0.003	0.001	0.001	0.001	0.013	0.0002
4	Na	mg/kg, d	1700	1700	3400	3500	1200	2600	330
5	K	mg/kg, d	1000	1600	3400	3100	1500	2500	430
6	Mn	mg/kg, d	58	70	130	120	98	140	80
7	Cr	mg/kg, d	15	290	70	960	110	45	3.3
8	Cu	mg/kg, d	35	35	40	75	2300	50	3.0
9	Ni	mg/kg, d	7.0	60	30	20	90	15	1.7
10	Zn	mg/kg, d	93	890	300	460	2100	190	60
11	Sb	mg/kg, d	4.2	240	4.0	85	190	220	0.5
12	As	mg/kg, d	0.8	2.0	2.6	12	1.4	1.4	0.5
13	Cd	mg/kg, d	0.15	1.5	0.2	1.3	5.2	0.12	0.12
14	Co	mg/kg, d	1.5	4.0	5.0	4.8	4.8	4.0	0.5
15	Pb	mg/kg, d	26	880	72	450	100	15	5.4
16	Mo	mg/kg, d	2.3	15	2.3	3.0	2.4	1.0	0.5
17	Se	mg/kg, d	0.95	0.7	0.85	0.59	0.5	0.75	0.5
18	Tl	mg/kg, d	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
19	V	mg/kg, d	4.5	160	14	14	20	18	0.8
20	Hg	mg/kg, d	0.1	0.05	0.2	0.2	0.05	0.1	0.02

The fine fraction and reject material were among the output streams measured to have a higher arsenic (As) content, i.e. 13.0 mg/kg and 10.0 mg/kg, respectively (Table 9). The input waste stream of C&D waste was measured to have an arsenic concentration of 15.0 mg/kg. Among the waste components, textile was found to have a higher concentration of arsenic (As). In the reject material, the mass fraction of textile was 3.4 wt. %. The concentration of cadmium (Cd) was found to be comparatively higher in the SRF and heavy fraction, i.e. 4.4 mg/kg and 4.0 mg/kg, respectively. Rubber material was measured to have higher cadmium content, i.e. 5.2 mg/kg, than the other waste components (Table 8). After rubber, plastic (hard) and textile were measured to contain 1.5 mg/kg and 1.3 mg/kg of cadmium, respectively. Among the output streams, the highest lead (Pb) content was measured in the reject material stream, i.e. 490 mg/kg (Table 9). In the elemental analysis, plastic (hard) was measured to have a higher lead (Pb) content than that measured in the other components of C&D waste (Table 8). The sizeable mass fraction of plastic (hard) in the reject material could have contributed to its higher lead (Pb) concentration. The SRF was measured to have the least concentration of lead (Pb) among the output streams, i.e. 42 mg/kg. The fine fraction was measured to contain a considerably higher mercury (Hg) concentration than the other streams. This could be linked with the fact that waste components with a high mercury content were shredded to a smaller particle size (< 15 mm) and sorted into the fine fraction stream by the screening process. Identification of rubber, plastic (hard) and textile (synthetic type) as a potential source of polluting elements and PTEs was in agreement with the findings of the previous research, i.e. SRF produced from C&IW (Chapter 3). The elemental analysis of the input and output streams produced in SRF production from C&D waste is given in Table 9.

From the elemental analysis of the output streams generated in SRF production from C&D waste, it was found that the reject material and fine fraction were the most contaminated in terms of carrying polluting elements and PTEs as compared with other output streams. The high recovery of wood, paper & cardboard and plastic (soft) from the input waste stream (C&D waste) into the SRF stream effectively reduced the content of polluting elements and PTEs in the SRF.

Table 9. Elemental analysis of input and output streams produced in the SRF production process: SRF produced from construction and demolition waste (mean value of three laboratory test sub-samples, dry basis of material) (Paper IV)

#	Element	Unit	Input waste	Reject material	Fine fraction	Heavy fraction	SRF
1	Cl	wt %, d	0.6	2.2	0.2	1.0	0.4
2	F	wt %, d	0.01	0.006	0.002	0.005	0.004
3	Br	wt %, d	0.005	0.008	0.002	0.001	0.003
4	S	wt %, d	0.7	0.7	2.8	0.3	0.3
5	Na	mg/kg, d	8370	8160	14400	7955	1470
6	K	mg/kg, d	6120	8060	13700	11570	1080
7	Ca	mg/kg, d	58050	56625	100800	46280	17150
8	Mg	mg/kg, d	5940	5920	8500	5150	1270
9	P	mg/kg, d	315	390	490	340	520
10	Al	mg/kg, d	18090	24280	37500	30010	4800
11	Si	mg/kg, d	51660	45000	46700	3700	12150
12	Fe	mg/kg, d	7560	10330	18200	11840	1275
13	Ti	mg/kg, d	1530	2130	2400	315	1275
14	Cr	mg/kg, d	135	180	130	100	35
15	Cu	mg/kg, d	660	950	140	715	350
16	Mn	mg/kg, d	270	250	680	280	70
17	Ni	mg/kg, d	38	68	45	22.5	8.0
18	Zn	mg/kg, d	400	595	500	310	175
19	Sb	mg/kg, d	42	70	10	5.8	84
20	As	mg/kg, d	15	10	13	4.5	6.6
21	Ba	mg/kg, d	260	645	680	390	138
22	Cd	mg/kg, d	1.5	1.0	0.6	4.0	4.4
23	Co	mg/kg, d	6.0	16	11	5.0	2.8
24	Pb	mg/kg, d	135	490	380	208	42
25	Mo	mg/kg, d	4.8	5.0	4.3	1.2	1.5
26	Se	mg/kg, d	1.8	2.2	4.0	3.0	2.7
27	Tl	mg/kg, d	0.5	0.5	0.5	0.6	0.5
28	Sn	mg/kg, d	13.5	95	26	126	14.7
29	V	mg/kg, d	23.4	38	48	33.5	4.0
30	Hg	mg/kg, d	0.2	0.08	0.7	0.05	0.2

4.2 Mass, energy and material balances of SRF production from C&D waste (Paper III)

A mass balance of SRF production was established for a batch of 74 tonnes of C&D waste used to produce SRF in an MT waste sorting plant. In the MT plant, the input C&D waste stream was classified/sorted into various output streams: SRF, fine fraction, heavy fraction, reject material, ferrous metal and non-ferrous metal. All the output streams were weighed. All the input waste material was recovered in the form of output streams with a very minor difference of material loss. Of the total input C&D waste material entering the process (by weight), 44 % of the material was recovered in the form of SRF, 6 % in the form of metals, 28 % was separated as fine fraction, 18 % as reject material and 4 % as heavy fraction. C&D waste understandably contained a high mass fraction of building material (i.e. stone/rock, sand, concrete etc.) and the major part of it was sorted out as the fine fraction (28 wt. %) in the screening section after primary shredding. The heavy fraction comprised of unshredded heavy particles of stone/rock, building blocks and some heavy pieces of metal and wood as well. The mass balance of SRF production from C&D waste is shown in Figure 10.

In the SRF production, the energy flow balance from the input waste stream (C&D waste) into the output streams was calculated based on the material flow analysis (MFA) approach (described in Section 2.8.) By using the law of energy conservation, the input energy content of C&D waste was calculated from the sum of the energy content of the output streams. In order to calculate the energy content of the output streams, the heating value (NCV, MJ/kg) of the stream (given in Table 7) was multiplied by the respective total mass of the stream (Figure 10). Energy recovered in the form of SRF was 74 % and 72 % of the total input energy content of C&D waste to the process on wet and dry basis of material respectively. The energy associated with the reject material, fine fraction, heavy fraction and metal streams was due to the mass fraction of combustible components in those streams. The difference between the measured and calculated values of the input energy content is calculated as an error value. The energy flow balance in the process streams of SRF production from C&D waste is shown in Figure 11.

Energy consumed in order to produce SRF from 74 tonnes of C&D waste was calculated (Paper III) in terms of in-plant operations and out-plant operations. In-plant operations comprised of unit operations/sorting techniques, the dust extraction system and material handling machinery (wheel loader and excavator) in the MT waste sorting plant. Out-plant operations included logistical means (vehicles) to collect C&D waste from its collection points and also delivery of output streams (SRF, metals, reject material, fine fraction and heavy fraction) to customers' premises. Energy consumed per unit tonne of feed (input waste stream of C&DW) for in-plant operations and out-plant operations was calculated as 50 kWh and 100 kWh respectively. This showed that the transportational means required to collect and deliver material, requires more energy than the energy required by the process/plant itself to produce SRF.

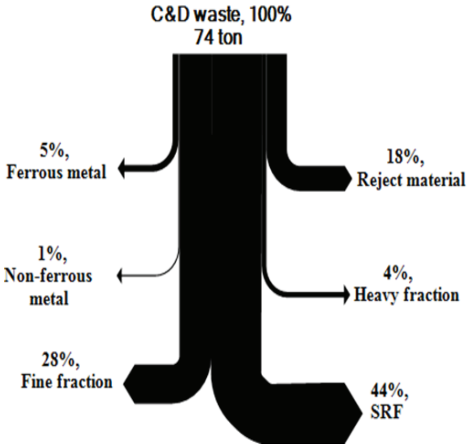


Figure 10: Mass balance of SRF production from construction and demolition waste (wet basis of material) (Paper III)

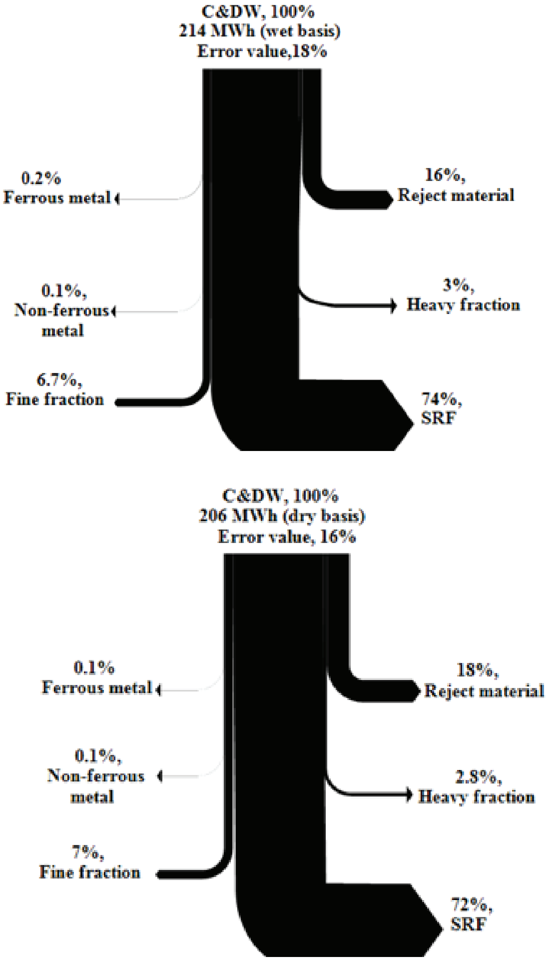


Figure 11: Energy flow balance in process streams of SRF production from construction and demolition waste (Paper III)

In the material balance of SRF production from C&D waste, the mass flow of the input stream's components, i.e. paper & cardboard, plastic (soft), plastic (hard), wood, rubber and foam, into the output streams was determined (Paper III). The mass of the component (on wet basis) in the streams (input and output) was calculated based on the composition of the streams (see Section 4.3) and the mass balance of SRF production (Figure 10). Recovery of plastic (soft) and paper & cardboard in the SRF was higher than the recovery of other waste components. Of the mass of plastic (soft) and paper & cardboard entering the process, 84 % and 82 % respectively were recovered in the SRF. Recovery of wood in the SRF was lower than expected. Of the mass of wood entering the process, 72% was recovered in the SRF. A considerable mass fraction of wood and paper & cardboard was found in the reject material, i.e. 8% and 8.5% respectively of their input mass to the process.

Components of paper & cardboard and wood found in the reject material were mainly those having a larger particle size (> 200 mm), irregular in shape (for example, some paper & cardboard components in rolled form) or heavy in weight/density (some unshredded components in primary shredding). Of the mass of textile and plastic (hard) entering the process, 70% and 68% respectively were recovered in the SRF and 16% and 22% were separated into the reject material. Plastic (hard) found in the reject material mainly consisted of PVC plastics. In the case of rubber material, the major mass fraction of input rubber was found in the reject material, i.e. 58%, and only 22% was recovered in the SRF. As described earlier (in the elemental analysis of waste components, Table 8), rubber, plastic (hard) and textile were measured to contain the highest concentration of polluting elements and PTEs among the waste components and, therefore, significant amounts of these components were sorted/separated out into the reject material by the NIR sorting units in the process.

4.3 Composition of input and output streams (Paper III)

The composition of the input and output streams of SRF production from C&D waste was determined through manual sorting of their respective combined samples (Table 2) into waste components such as paper & cardboard, wood, plastics, metals, textile rubber, foam and inert material. In the composition of C&D waste, mass fraction of wood, building material (i.e. stone/rock/building blocks, sand and concrete etc.) and fines was 23.6 %, 14.2 % and 16.6 %, respectively. The mass fraction of paper & cardboard and plastics (soft and hard) in C&D waste was 12 % and 9.6 %, respectively. In Finland, C&D waste contains more combustible material (especially wood) than in central Europe. The SRF derived from C&D waste was enriched in wood, paper & cardboard and plastics. In the composition of SRF, the mass fraction of wood, paper & cardboard and plastics (soft and hard) was 38.0 %, 22.0 % and 16 %, respectively. The reject material stream mainly comprised building material, rubber and glass. A considerable mass fraction of wood was also found in the reject material stream. The composition of input and output streams in SRF production from C&D waste is given and discussed in Paper III.

The energy-based composition of SRF produced from C&D waste was calculated from the composition of SRF (on mass basis) and NCVs of the waste components. In order to calculate the energy-based composition of SRF, the mass fractions of the SRF components were multiplied by their respective net calorific values. The majority of the energy of the SRF was contained by wood, i.e. 37% of the total energy of the SRF. Plastics (soft and hard) and paper & cardboard accounted for 31% and 18% of the total energy content of SRF, respectively. The energy-based composition of SRF produced from C&D waste is shown in Figure 12.

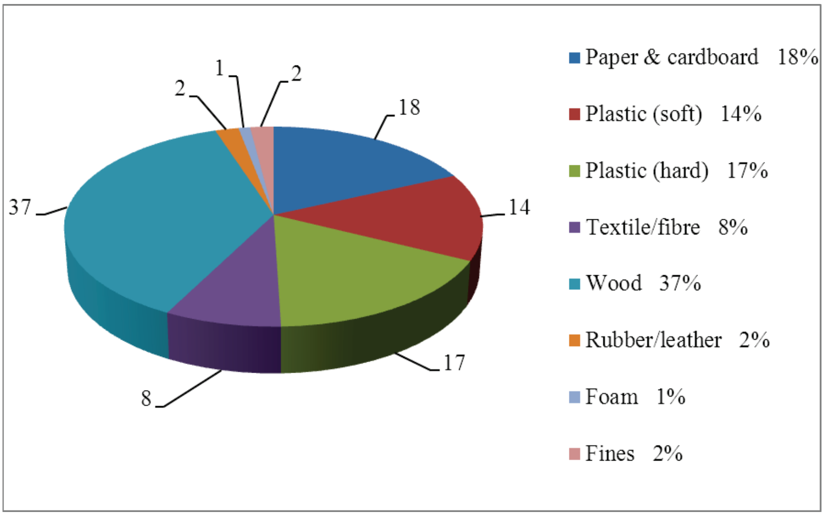


Figure 12: Energy-based composition of SRF produced from construction and demolition waste (Paper III)

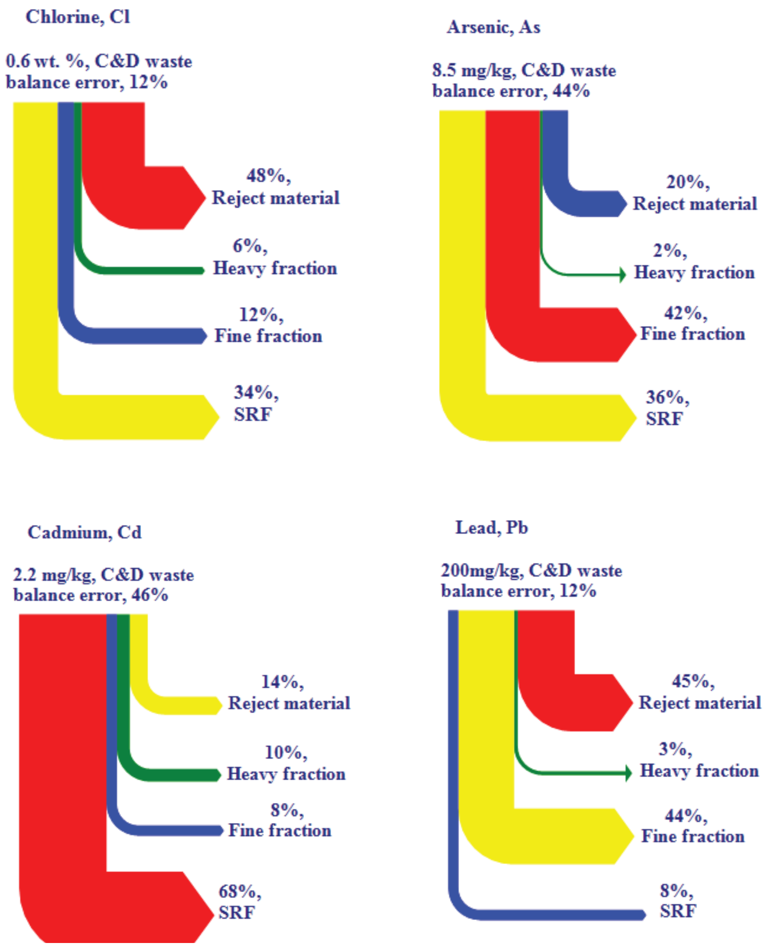
4.4 Elemental balance of SRF production from C&D waste (Paper IV)

In the elemental balance (shown in Figure 13), a higher mass fraction of the input chlorine (Cl) and lead (Pb) was found in the reject material than in other output streams. Of the chlorine and lead content entering the process (by weight), 48 % and 45 % respectively were concentrated in the reject material. In the case of arsenic (As) and mercury (Hg), the fine fraction became the most contaminated of the output streams. Of the input arsenic and mercury content to the process, 42 % and 64 % respectively was found in the fine fraction stream. In contrast, a higher mass fraction of the input cadmium (Cd) entering to the process, was found in the SRF than in the other output streams, i.e. 68 %. The elemental balance of SRF production from C&DW is shown in Figure 13.

The high recovery of paper & cardboard, plastic (soft) and wood from the input waste stream (C&D waste) in the SRF stream effectively reduced the concentration of polluting elements and PTEs in the SRF. On the other hand, the high mass fraction of input rubber, plastic (hard, mainly PVC plastics) and textile (especially synthetic type) was sorted into the reject material and thus waste components, especially those containing a high chlorine content, were routed into the reject material stream. The high mass flow of arsenic (As) and mercury (Hg) into the fine fraction stream was linked with the fact that the majority of components with a high concentration of the said elements were shredded to a smaller particle size (< 15 mm) in primary shredding and screened out in the screening section of the process. In the elemental analysis of waste components (Table 8), textile was measured to have a higher concentration of arsenic (As) than the other waste components. Among the waste components, plastic (soft) and textile were measured to contain a higher mercury (Hg) concentration. In the process, it was noticed that a relatively low moisture content (i.e. 14.0 wt. %) of the input waste stream (C&D waste) affected (positively) the proper sorting of combustible components (especially paper & cardboard, wood and soft plastic) into SRF by air classifier. Sorting of highly chlorinated plastic (PVC plastic) and rubber into the reject material was performed by NIR sorting technology.

The sorting of highly chlorinated waste components into the reject material and the high recovery of combustible components (paper & cardboard, wood and soft plastics) were noticed to be very efficient through the positive sorting of the NIR sorting unit. A lower moisture content (i.e. 14.0 wt. %) of the input stream of C&D waste could have facilitated the better sorting of waste components performed by air classifiers and NIR sorting units in the process, as this was not observed in the case of SRF produced from C&IW with a higher moisture content (25.6 wt. %). However, there was still a noticeable mass fraction of combustibles (especially wood and paper & cardboard) in the reject material (section 4.3), most of these components were larger in particle size (> 200 mm) or irregular in shape (i.e. not properly shredded in primary shredding). Recovery of these combustibles into the SRF stream could have further reduced the concentration of polluting elements and PTEs and enhanced the yield of SRF. The higher mass flow of cadmium (Cd) in the SRF compared with other output streams reflected the fact that waste components containing a high concentration of cadmium found their way through the unit operations (especially the air classifier and NIR sorting unit) into the SRF stream. In the elemental analysis of waste components (Table 8), rubber was measured to contain 5.2 mg/kg of cadmium, which was higher than in other components. It could be that some lightweight components of rubber with a high concentration of cadmium (Cd) were classified by air classifier and put into the SRF stream. The other possibility could be that components containing high levels of cadmium might have been picked by the NIR sorting unit and put into the SRF stream (as due to the black colour of the conveyor belt the NIR sorting unit does not recognize components that are black/dark in colour).

The specific load of polluting elements and PTEs in unsorted C&D waste contributed by various waste components was calculated (Paper IV) based on the composition of C&D waste (Section 4.3) and the elemental analysis of waste components (Table 8). In unsorted C&D waste, plastic (hard), rubber and textile shared the maximum chlorine load, i.e. 40 %, 38 % and 15 %, respectively, of the total chlorine load. Among the waste components, textile carried a far higher load of arsenic (As) in unsorted C&D waste, i.e. 45% of the total arsenic load. The load of cadmium in unsorted C&D waste was mainly carried by rubber, i.e. 58% of the total load. Plastic (hard) was also calculated to carry 20 % of the cadmium load and it was also found to contribute the major load of lead (Pb), i.e. 65 % of the total load of lead in unsorted C&D waste. Textile carried about 20 % of the load of lead (Pb). The specific elemental load contribution by waste components in unsorted C&D waste is presented and discussed in Paper IV.



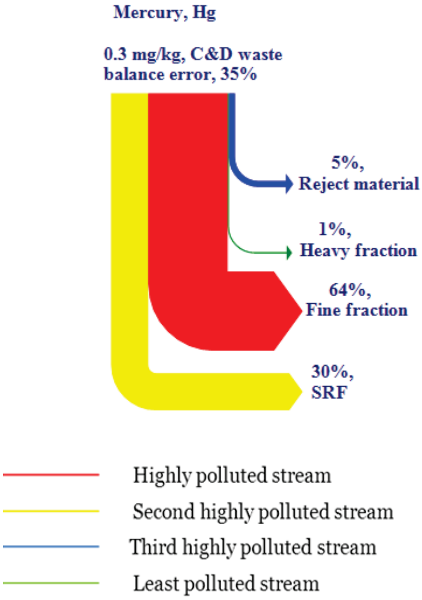


Figure 13: Elemental balance of SRF production from construction and demolition waste (Paper IV)

Major findings

- In an industrial-scale SRF production from construction and demolition waste, of the the total input waste material to the process, 44 wt. % was recovered in the form of SRF and 6 wt. % as metals (ferrous and non-ferrous), 28 wt. % was separated as fine fraction, 18 wt. % as reject material and 4 wt. % as heavy fraction. Energy recovered in the form of SRF was 74% of the feedstock energy content. The energy consumed to process 74 tonnes of C&D waste in the MT plant to produce SRF was calculated in terms of in-plant and out-plant operations. Energy consumed by in-plant and out-plant operations per unit tonne of feedstock was 50 kWh and 100 kWh, respectively.
- C&D waste mainly consisted of wood, building material, paper & cardboard and metals components. In the composition (weight-based) of C&D waste, the mass fraction of wood, paper & cardboard and metals was 23.6%, 12% and 10%, respectively. The composition (weight-based) of SRF derived from C&D was dominated by wood, paper & cardboard and plastics, i.e. 38%, 22% and 16%, respectively. The reject material stream mainly contained inert material (i.e. stone/rock, concrete and building blocks etc.), highly chlorinated rubber and PVC plastic.
- In the elemental balance of SRF production from C&D waste, the majority of the chlorine (Cl), lead (Pb), mercury (Hg) and arsenic (As) (in the feedstock) entering the process was separated/sorted into non-SRF

streams, i.e. reject material, fine fraction and heavy fraction. A higher mass of chlorine (Cl) and lead (Pb) entering the process was found in the reject material as compared with other output streams i.e. 48% and 45% respectively of the input chlorine and lead content entering the process was found in the reject material. The majority of the arsenic (As) and mercury (Hg) content travelled to the fine fraction, i.e. 42% and 64%, respectively. In the case of cadmium, most of it, i.e. 68%, was found in the SRF.

- Among the components of C&D waste, rubber, plastic (hard) and textile (especially synthetic type) were identified as a potential source of polluting elements and PTEs. In contrast, wood, paper & cardboard and plastic (soft) were found to have the lowest content of polluting elements and PTEs.

5 Material and energy balance of SRF production from municipal solid waste

(Papers V and VI)

The material and energy balance of solid recovered fuel (SRF) production from municipal solid waste (MSW) is presented in this chapter. The SRF was produced on industrial scale from a batch of 30 tonnes of MSW in a mechanical treatment (MT) waste sorting plant. The stream of MSW used to produce SRF was energy waste collected from households (Paper V). The energy waste was source-separated at the household level and contained more than 75 wt. % of energy-related waste components: paper & cardboard, plastics, textile, wood, rubber, foam material etc. along with a small wt. % of non-energy-related waste components such as inert material (metals, glass, and stones) and food waste, due to some mis-sorting. The results presented in this chapter include mass, energy, material (Paper V) and elemental (Paper VI) balances of SRF production. The mass flow of polluting elements and PTEs in SRF production is determined (Paper VI) based on the elemental balance of SRF production. In MSW, potential source components for polluting elements and PTEs are identified based on the elemental analysis of waste components (Paper VI). The specific load of various elements in MSW contributed by waste components is determined (Paper VI) based on the composition of MSW (Paper V) and elemental analysis of components (Paper VI). The whole of this work is presented in appended Papers V and VI.

5.1 Proximate & ultimate and elemental analysis of process streams and waste components: SRF produced from MSW (Paper V and Paper VI)

The net calorific value of SRF derived from MSW was measured as 20.2 MJ/kg (a.r. basis). This high calorific value of the SRF was due to the significant contribution of paper & cardboard and plastics. Plastics were reported as major contributors to the high calorific values of the fuel (Rotter et al., 2004). The biomass content as a share of bio carbon measured in the SRF was 50.8%. Paper & cardboard and wood were the major contributors to the biomass content in this SRF. Biogenic components of SRF in the range of 40%–80% were reported in the literature (Hansen et al., 1998). The high ash content in the heavy fraction, fine fraction and reject material streams was due to the high mass fraction of incombustible impurities (especially stone/rock, glass and to some extent metals). The moisture content in the fine fraction stream was higher than in other streams, owing to the biowaste (i.e. food waste) components in it. The laboratory analysis of the streams (input and output) produced in SRF production from MSW (energy waste collected from households) is given in Table 10.

Table 10: Laboratory analysis results of process streams in SRF production from MSW (energy waste collected from households) (mean value of three laboratory test sub-samples) (Paper V)

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	NCV (d.) MJ/kg
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[c]	26.8	32.5	n.a.	n.a.	40.3	5.2	0.9	0.5	16.3	12.0	16.8
Fine f.[d]	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 household

[c] Reject represents the reject material stream

[d] Fine f. and Heavy f represent the fine fraction stream and heavy fraction stream respectively

The source of polluting and PTEs in unsorted MSW was identified (Paper VI) based on the elemental analysis of components of MSW (Table 11). Rubber was identified as a potential source of chlorine (Cl), containing 8.0 wt. % of chlorine. Rubber material also contained components of rubber shoes. The high concentration of chlorine in rubber was in agreement with the previous results obtained from elemental analysis of the components of C&IW and C&D waste. Among waste components, it was recommended to direct shoes away from the SRF stream (Velis et al., 2013) as it was one of the components having a high chlorine content (Velis et al., 2012). Food waste was measured to have 1.2 wt. % of chlorine (Cl). The chlorine concentration in food waste could be due to food containing salt in the food waste components. Among the waste components, textile was measured to contain a higher concentration of bromine (Br). Flame-retardant textiles have been reported (Vainikka et al., 2011; Vainikka and Hupa, 2012; Wua et al., 2014) as a potential source of bromine. A higher concentration of lead (Pb) and cadmium (Cd) was found in plastic (hard) than in other components of MSW. Textile and rubber were measured to contain 0.2 mg/kg of mercury (Hg) each, which was higher than that found in other components. The elemental analysis of the components of MSW (energy waste collected from households) is given in Table 11. Among the output streams, reject material was measured to contain 2.7 wt. % of chlorine (Cl), which was higher than that measured in other output streams (see Table 12). The high chlorine concentration of the reject material was due to the high mass fraction of rubber and plastic (PVC plastic) contained in it. The chlorine (Cl) content of the input waste stream (MSW) was measured as 1.5 wt. %. In the SRF produced from MSW, the chlorine content was reduced to more than half. The bromine (Br) content in the reject stream was measured to be more than in other streams. Most likely, the bromine concentration was due to the textile component, especially flame-retardant textiles. The fine fraction stream was found to contain 8.0 mg/kg, d. of arsenic (As) and was higher than in other streams. This could be due to waste components containing a high concentration of arsenic (As) and shredded in primary shredding to a small particle size (< 15 mm) and screened out as fines in the screening section. The fine fraction and reject material were measured to contain 180 mg/kg and 160 mg/kg lead (Pb) content, respectively. Among the waste components, plastic (hard) was measured to contain a higher level of lead (Pb), at 500 mg/kg. The mercury (Hg) content in the fine fraction stream was found to be much higher than in the other output streams i.e. 0.8 mg/kg.

Table 11. Elemental analysis of components of MSW (energy waste collected from households) (mean value of three laboratory sub-sample tests, dry basis of material) (Paper VI)

#	Element	Unit	Paper & cardboard	Plastic (hard)	Plastic (soft)	Textile	Rubber	Foam	Wood	Food waste
1	Cl	wt %, d	0.15	1.6	0.83	1.1	8.0	0.75	0.05	1.2
2	F	wt %, d	0.002	0.003	0.004	0.004	0.001	<0.001	<0.001	0.002
3	Br	wt %, d	0.001	0.001	0.001	0.008	0.001	0.001	0.001	0.001
4	Na	mg/kg, d	1400	570	1300	3700	980	800	220	11200
5	K	mg/kg, d	940	440	1200	1500	420	670	710	7600
6	Mn	mg/kg, d	30	25	40	40	30	25	50	60
7	Cr	mg/kg, d	15	68	40	5300	88	38	7.0	38
8	Cu	mg/kg, d	30	24	37	77	1400	40.0	4.7	140
9	Ni	mg/kg, d	6.0	25	18	30	32	17	3.3	14
10	Zn	mg/kg, d	47	170	160	310	3800	3800	20	110
11	Sb	mg/kg, d	3.0	56	5.0	62	170	2.8	1.8	3.4
12	As	mg/kg, d	0.43	0.61	1.0	2.4	0.6	0.5	0.1	0.8
13	Cd	mg/kg, d	1.2	9.0	0.5	3.1	1.5	0.5	0.12	0.1
14	Co	mg/kg, d	1.0	2.0	1.4	2.4	4.8	1.6	<0.5	1.4
15	Pb	mg/kg, d	12.0	500	20	63.0	370	38.0	3.0	120
16	Mo	mg/kg, d	0.9	1.6	20	4.0	2.2	1.3	0.5	1.8
17	Se	mg/kg, d	0.8	1.2	0.8	1.0	1.0	1.6	<0.53	1.1
18	Tl	mg/kg, d	<0.5	<0.5	<0.5	0.5	0.5	<0.5	<0.5	-
19	V	mg/kg, d	4.1	2.2	6.5	6.2	4.3	5.0	0.1	4.3
20	Hg	mg/kg, d	0.05	0.05	0.1	0.2	0.2	0.1	0.05	0.05

The mercury content in the reject stream was also on the higher side, i.e. 0.5 mg/kg. The elemental analysis of various streams produced in SRF production produced from MSW (energy waste collected from households) is given in Table 12. Among the waste components of MSW, rubber, plastic (hard) and textile (especially the synthetic type) were identified as a potential source of polluting elements and PTEs. In contrast, wood, paper & cardboard, plastic (soft) and foam were identified as containing the lowest amount of polluting and PTEs among the components of MSW.

Table 12. Elemental analysis of input and output streams produced in SRF production from MSW (energy waste collected from households) (mean value of three laboratory sub-sample tests, dry basis of material) (Paper VI)

#	Element	Unit	Input waste (MSW)	Reject material	Fine fraction	Heavy fraction	SRF
1	Cl	wt %, d	1.5	2.7	1.1	0.04	0.6
2	F	wt %, d	0.01	0.05	0.0001	0.002	0.01
3	Br	wt %, d	0.002	0.01	0.0001	0.001	0.004
4	S	wt %, d	0.2	0.5	1.0	0.1	0.2
5	Na	mg/kg, d	7920	9190	18880	7110	1590
6	K	mg/kg, d	3530	4475	8500	13870	920
7	Ca	mg/kg, d	30625	36600	56260	82350	28925
8	Mg	mg/kg, d	2960	3140	6420	4560	1390
9	P	mg/kg, d	380	980	1230	310	340
10	Al	mg/kg, d	12400	15990	23320	48110	6260
11	Si	mg/kg, d	41500	40410	54750	32490	9240
12	Fe	mg/kg, d	6680	3760	11610	8340	1390
13	Ti	mg/kg, d	2480	2570	2740	4390	1990
14	Cr	mg/kg, d	150	450	210	80	370
15	Cu	mg/kg, d	1240	3865	690	710	270
16	Mn	mg/kg, d	105	415	235	175	55
17	Ni	mg/kg, d	50	250	105	30	11
18	Zn	mg/kg, d	560	1380	735	50	230
19	Sb	mg/kg, d	70	140	80	2.2	540
20	As	mg/kg, d	3.4	4.0	8.0	4.4	0.7
21	Ba	mg/kg, d	468	490	1510	360	280
22	Cd	mg/kg, d	1.0	1.0	2.2	0.2	0.7
23	Co	mg/kg, d	3.6	6.0	8.5	4.4	3.4
24	Pb	mg/kg, d	280	160	180	25	30
25	Mo	mg/kg, d	12.4	8.0	20	1.8	3.2
26	Se	mg/kg, d	1.2	1.4	2.2	3.8	0.5
27	Tl	mg/kg, d	0.5	0.5	0.5	0.4	0.5
28	Sn	mg/kg, d	26	68	40	8.0	12
29	V	mg/kg, d	20	11.0	25.0	54	8.0
30	Hg	mg/kg, d	0.15	0.5	0.8	0.1	0.1

5.2 Mass, energy and material balances of SRF production from MSW (Paper V)

The mass balance of the SRF production was established for a batch of 30 tonnes of MSW fed to the MT waste sorting plant. All the output streams produced from input waste were weighed. The input waste material was recovered in the form of output streams with a negligible mass difference. In the process, of the total input MSW (by weight), 72 % of the material was recovered in the form of SRF, 3 % in the form of metals, 11 % was separated as reject material, 12 % as fine fraction and 2 % as heavy fraction. The mass balance of the SRF production from MSW is shown in Figure 14.

The energy flow balance in the process streams of SRF production was determined based on the law of energy conservation and was calculated using the MFA approach (described in section 2.8). The energy balance of the input waste stream was calculated from the sum of the energy content of the output streams. The energy content of the output streams was calculated by multiplying their NCV (MJ/kg, dry and as-received basis, given in Table 10) by their respective mass (Figure 14 and moisture content of streams given in Table 10 aswell). The difference between the measured and calculated energy value of the input energy stream (MSW) is given as an error value. Very high levels of energy were recovered from the input energy content of MSW, i.e. 86 %, in the form of SRF. The energy flow balance in process streams of SRF production from MSW is shown in Figure 15. The energy consumed in processing the batch of 30 tonnes of MSW in the MT plant to produce SRF was calculated in terms of in-plant operations and out-plant operations. In-plant operations included the unit operations/sorting techniques (described in Section 2.2), dust extraction system and material handling machinery (wheel loader and excavator) used in the MT plant. Out-plant operations included the logistical means (i.e. vehicle/trucks/lorries) used to collect MSW from its collection points and deliver it to the processing plant location, it also included the transportation delivery of the output streams (i.e. SRF and others) to the customers' premises. The energy consumed per unit tonne of feed for in-plant operations and out-plant operations was calculated as 70 kWh and 242 kWh respectively (Paper V).

In the material balance of SRF production from MSW, a very high mass fraction of paper & cardboard, wood and plastic (soft) was recovered in the SRF, i.e. 88 %, 90 % and 85 %, respectively. The recovery of textile in the SRF was also on the high side, i.e. 82 % of its input mass. Of the input plastic (hard) and rubber, 14 % and 55 % respectively was found in the reject material. The plastic (hard) found in the reject material was mainly PVC plastic components and the rubber was highly chlorinated. These were routed away by the NIR sorting units from the input waste stream into the reject material. The material balance of SRF production from MSW (energy waste collected from households) is presented and discussed in Paper V.

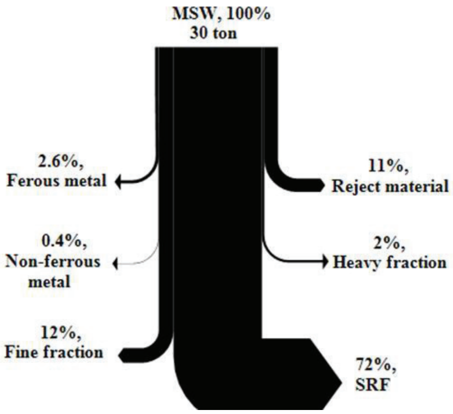


Figure 14. Mass balance of SRF production from MSW (energy waste collected from household) (wet basis) (Paper V)

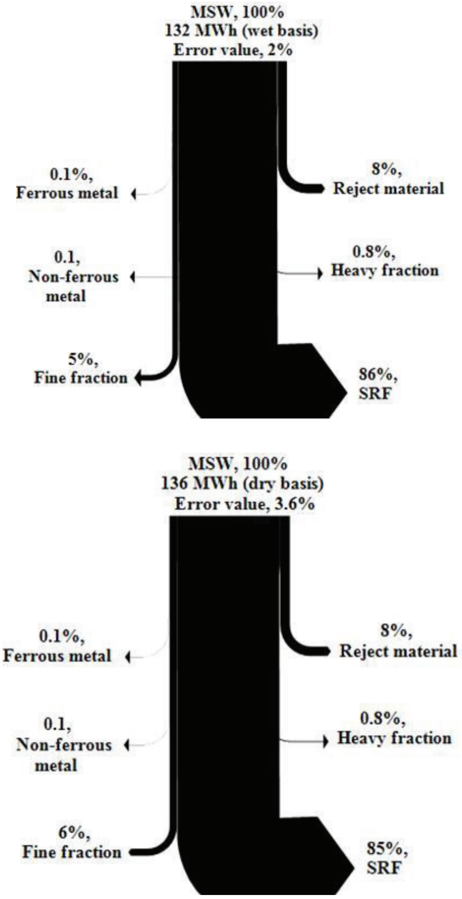


Figure 15: Energy flow balance in process streams of SRF production from MSW (energy waste collected from household) (Paper V)

5.3 Composition of input and output streams

In the composition (on weight basis) of MSW, plastics and paper & cardboard were the dominant components at 28.6 % and 24.5 %, respectively. The SRF produced from MSW was highly enriched with plastics and paper & cardboard. In the SRF, the mass fraction of plastic (soft and hard) and paper & cardboard was 32.6 % and 30 %, respectively. The mass fraction of textile in the SRF was 10.0 %. The reject material stream mainly comprised rubber, plastic (hard), textile and biowaste (especially food waste). As described earlier, most of the rubber and plastic (hard) components found in the reject material were highly chlorinated and PVC plastics. Textile components separated in the reject material were mainly synthetic type (containing a relatively high chlorine and bromine content), larger in particle size (< 200 mm) or in rolled form (non-shredded rolls). The fine fraction stream was found mainly to contain glass, biowaste (food waste) and stones i.e. 22.2 %, 20 % and 16.8 %, respectively. The biowaste found in the fine fraction stream was shredded in primary shredding (< 15 mm) and screened out in the screening section of the process. The composition of the input and output streams of SRF production from MSW is given and discussed in Paper V.

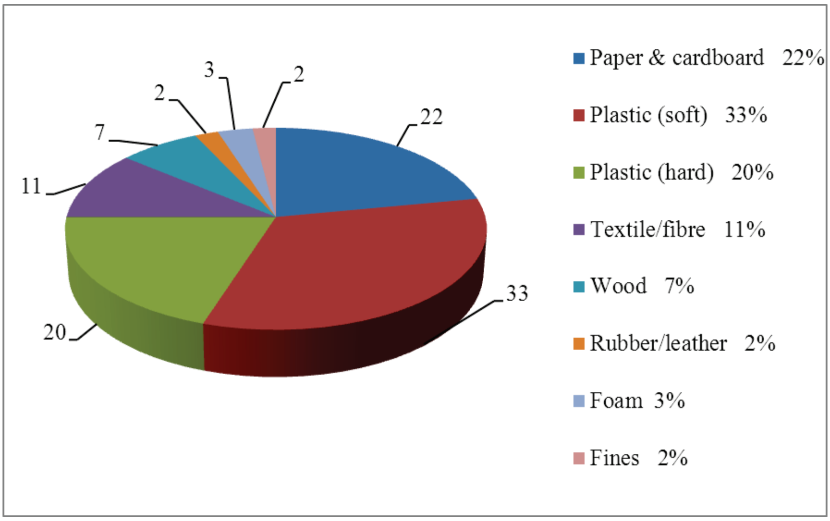


Figure 16: Energy-based composition of SRF produced from MSW (energy waste collected from household) (Paper V)

The energy-based composition of the SRF produced from MSW was calculated from its composition on a mass basis and the net calorific values of the waste components. The energy content of the SRF was dominated by plastic (soft), paper & cardboard and plastic (hard) i.e. 33 %, 22 % and 20 %, respectively. Textile carried 11 % of the energy content of the SRF. The energy-based composition of the SRF produced from MSW is shown in Figure 16.

5.4 Elemental balance of SRF production from MSW (Paper VI)

In the SRF production, a higher mass fraction of the input chlorine (Cl) and cadmium (Cd) content to the process was found in the SRF than in other output streams i.e. 55 %, 62 %, respectively. While a higher mass fraction of input arsenic (As) and mercury (Hg) content to the process was found in the fine fraction stream i.e. 45 % each. Lead (Pb) was found comparatively homogeneously distributed among the SRF, fine fraction and reject material streams i.e. 38 %, 32 % and 28 %, respectively, of the lead (Pb) content entering the process. The elemental balance of SRF production from MSW (energy waste collected from households) is shown in Figure 17. The difference in the measured and calculated values of the input element concentration is calculated as a balance error.

In the SRF production, the components of the input waste stream were sorted into the various output streams based on material properties such as particle size, density/weight, magnetic properties, and infrared (IR)/spectral properties. Based on the results of the composition of the process streams (see Section 5.3), the elemental analysis of the components of the input waste stream (Table 11) and the elemental balance of SRF production process (Figure 17), certain factors were identified which caused the higher mass flow of chlorine and cadmium in the SRF stream as described below.

In the elemental analysis of the waste components, rubber, plastic (hard) and textile (synthetic) were identified as potential sources of chlorine (Cl). Plastic (hard) waste components were also measured to have a higher cadmium (Cd) content than the other waste components (see Table 11). In the SRF production, to a certain extent, waste components with a high chlorine and cadmium content were not separated and prevented from entering the SRF stream. Even though a high mass fraction of rubber and PVC plastic was separated into the reject material there were still certain lightweight waste components (of rubber, plastic or textile having a high chlorine and cadmium content) separated into the SRF stream by the air classifier.

On the other hand, the NIR sorting unit could have picked out certain waste components (with a high chlorine and cadmium content) and put them into the SRF stream. One observation related to this issue might be the lack of capacity or proper/regular maintenance checks of the NIR sorting unit (especially the air nozzles). It could also be related to the non-steady flow rate of waste material (sometimes there could be sudden peaks of material flow from the sorting units due to the uneven material feeding at the start of the process) passing through the NIR sorting unit on the conveyor belt. Increasingly, NIR sorting technology capable of removing highly chlorinated plastic polymers is being adopted in newly built SRF production plants (Roos and Peters 2007; Schirmer et al., 2007) but improvements in this sorting technology are necessary for full operational scale (Pieber et al., 2012).

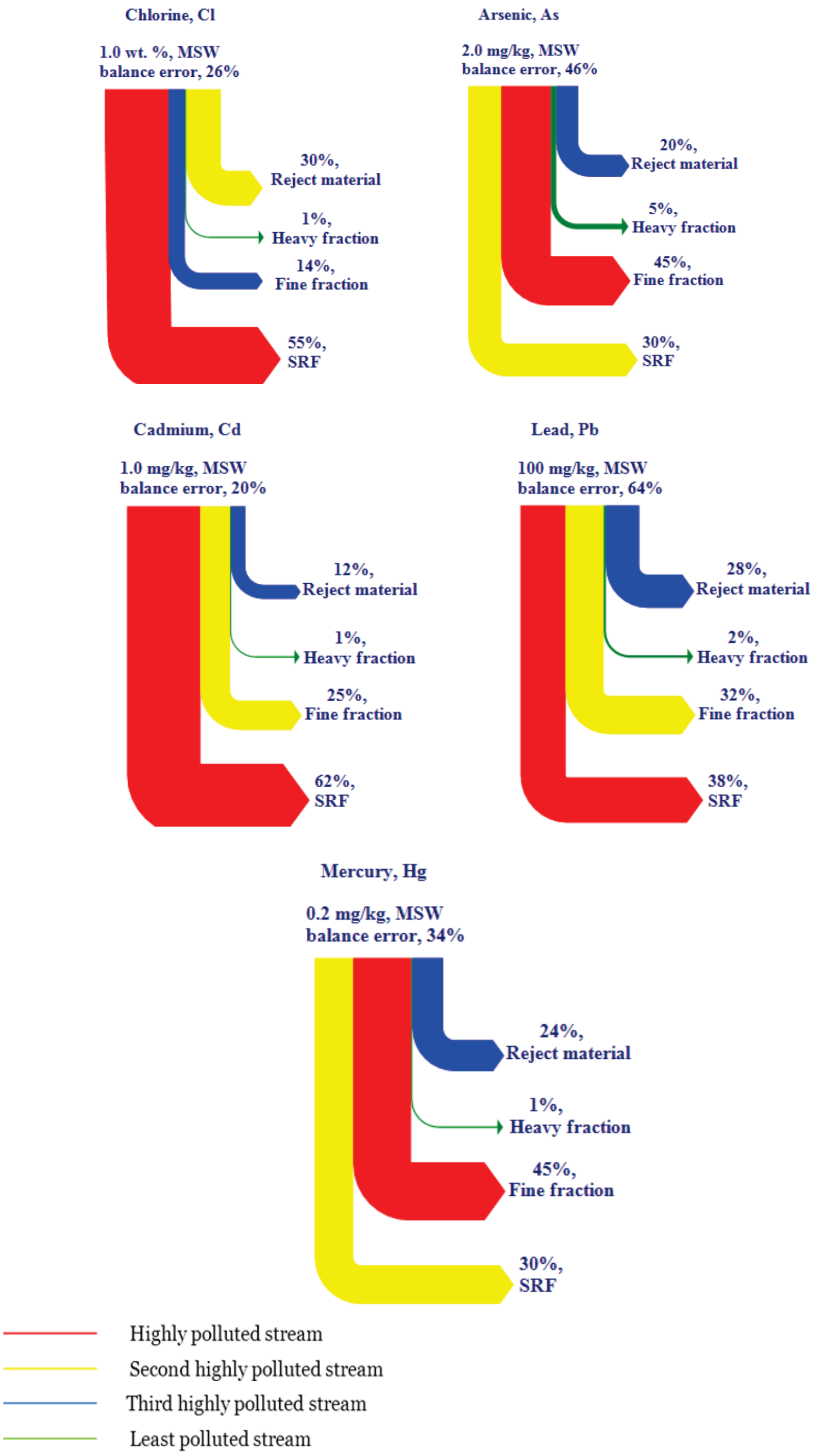


Figure 17: Elemental balance of SRF production from MSW (energy waste collected from household) (Paper VI)

In the case of mercury and arsenic, a higher mass flow of their respective input content was found in the fine fraction stream. This might be linked with the fact that waste components in the input waste stream containing mercury and arsenic were shredded to a smaller particle size (<15 mm) in the primary shredding unit and screened out as fine fraction.

The specific load of polluting elements and PTEs contributed by the various waste components in unsorted MSW was calculated (Paper VI) based on the composition of MSW (section 5.3) and the elemental analysis of the waste components (Table 11). Rubber material carried the maximum chlorine load, i.e. 40 %, of the total chlorine load in unsorted MSW. Plastic (hard) was found to carry 20% of the chlorine load in MSW. Among the waste component, textile and plastic (soft) shared about a 60% load of arsenic (As) in unsorted MSW, i.e. 35% and 25%, respectively, of the total arsenic load. The load of cadmium (Cd) in unsorted MSW was mainly contributed by plastic (hard), i.e. 58% of the total load. Plastic (hard) was also found to carry the major load of lead (Pb), i.e. 62 % of the total load of lead in MSW. Textile, plastic (soft) and rubber were among the prominent contributors of the mercury (Hg) load, i.e. 26%, 24% and 12%, respectively, of the total mercury load in unsorted MSW. The specific elemental load contribution by waste components in unsorted MSW is presented and discussed in Paper VI.

Major findings

- Solid recovered fuel was produced from municipal solid waste (energy waste collected from households) in an industrial-scale mechanical treatment (MT) waste sorting plant. In this process, a significantly large amount of material was recovered in the form of SRF. Of the MSW input to the process, 72 wt. % was recovered as SRF, 3 wt. % as metals (ferrous/non-ferrous) for recycling and the rest was separated as fine fraction, reject material and heavy fraction. Of the energy content input to the process in the form of MSW, 86 % was recovered in the form of SRF. The energy consumed per unit tonne of feedstock was calculated as 70 kWh and 242 kWh by in-plant operations and out-plant operations, respectively.
- In the composition of MSW (energy waste collected from households), plastics and paper & cardboard shared the major fraction of it, i.e. 28.6 wt. % and 24.5 wt. %, respectively. The composition of SRF produced from MSW was further enriched with plastic and paper & cardboard, i.e. 32.6 wt. % and 30.0 wt. %, respectively. The major waste components in the reject material stream were rubber, plastic (hard, PVC plastic) and inert material (glass, stone and fines).
- In the elemental balance of SRF production, among the output streams, higher mass flow of the input chlorine (Cl) and cadmium (Cd) content was found in the SRF, i.e. 55 %, 62 %, respectively. Of the input

concentration of arsenic (As) and mercury (Hg), the highest mass flow was found in the fine fraction, i.e. 45 % each. Lead (Pb) was found comparatively evenly distributed among the SRF, fine fraction and reject material, i.e. 38 %, 32 % and 28 %, respectively, of the lead (Pb) content entering the process.

- In the elemental analysis of components of MSW, rubber, plastic (hard) and textile (especially synthetic type) were identified as a potential source of polluting and PTEs. Conversely, paper & cardboard, wood and plastic (soft) were found to have the lowest content of polluting elements and PTEs.

6 Comparison of major results of SRF production from C&IW, C&DW and MSW

(Paper I – VI)

In this chapter, the major results of the SRF production from three different types of waste material: C&IW, C&DW and MSW, are compared and discussed. The results include the quality and material & energy yield of SRF, the source of polluting and potentially toxic elements (PTEs) in different waste streams, the energy consumed to produce SRF, the energy yield and mass flow of polluting and PTEs in the SRF production.

6.1 Qualitative classification of SRF

Classification of the SRF produced from three different types of waste material was made as per CEN standards (EN 15359) for SRF based on the limit values of three important fuel properties (given in Table 1): net calorific value (NCV, a.r.), chlorine content (%, dry) and mercury content (mg/MJ, a.r.). The classification of the SRF produced from various waste materials is given in Table 13.

Table 13. Classification of SRF produced from different types of waste material

SRF produced from	NCV MJ/kg, a.r.		Chlorine (Cl) wt. %, d		Mercury (Hg) mg/MJ, a.r.	
C&IW	18.0	Class 3	0.62	Class 3	0.004	Class 1
C&DW	18.0	Class 3	0.44	Class 2	0.009	Class 1
MSW[a]	20.2	Class 2	0.58	Class 2	0.004	Class 1

[a] MSW: Energy waste collected from households

The net calorific value of the SRF produced from C&IW, C&DW and MSW (energy waste collected from households) was mainly due to plastics contribution in it. There was a greater plastic mass fraction in the SRF produced from MSW than in with that produced from C&IW and C&D waste. Among the waste components, wood was measured to contain the lowest chlorine (Cl) content. In the case of SRF produced from C&D waste, the high mass fraction of wood effectively reduced the chlorine (Cl) content to 0.4 wt. %, d. The mass fraction of plastics in SRF produced from C&DW was lower than in SRF produced from C&IW and MSW.

6.2 Comparison of product yield

A higher yield of material and energy was obtained from SRF produced from MSW than that produced from C&IW and C&D waste. A comparatively lower moisture content and better particle size distribution (in terms of particle size and shape) and fewer impurities (i.e. rubber, PVC plastics and metals etc.) in the incoming MSW as compared with C&IW and C&DW were among the main reasons observed, which facilitated the higher yield of SRF. The material and energy yield of SRF production from C&IW, C&DW and MSW are given in Table 14.

Table 14. Material and energy yield of SRF production from C&IW, C&DW and MSW

SRF produced from	Material yield as SRF wt. %	Energy yield as SRF MWh, %
C&IW	62	75
C&DW	44	74
MSW[a]	72	86

[a] MSW: Energy waste collected from households

As discussed earlier, in SRF production from C&IW and C&DW, a significant mass fraction of combustibles (paper & cardboard and wood) was found in the reject material stream, reducing the yield of material and energy in the form of SRF. Combustibles (paper and cardboard and wood) found in the reject stream mainly consisted of waste components with a large particle size (> 200 mm), highly moist (> 25 wt. %) or irregular in shape (in bundle or unshredded form). The recovery of the said components from the reject material into the SRF stream could have effectively enhanced the material and energy yield of the SRF.

6.3 Energy consumed to produce SRF and power available from SRF

The energy consumed to produce SRF from C&IW, C&DW and MSW was calculated (Paper I, Paper III, Paper V) in terms of in-plant operations and out-plant operations (see Section 3.2, 4.2 and 5.2). The power available from the SRF produced from the said three types of waste material was calculated by using a power production efficiency of 31 % of a Finnish combined heat and power (CHP) gasification plant. The result of the energy consumption to produce SRF and power available from the SRF is shown in Figure 18 in the form of a comparison for SRF produced from C&IW, C&DW and MSW (energy waste collected from households).

In each case the energy consumed by out-plant operations was higher than consumed by the in-plant operations. Energy consumed in out-plant operations for MSW was higher than that consumed for C&IW and C&D waste. This was due to the requirement for more logistical means to collect waste from households from various waste collecting points.

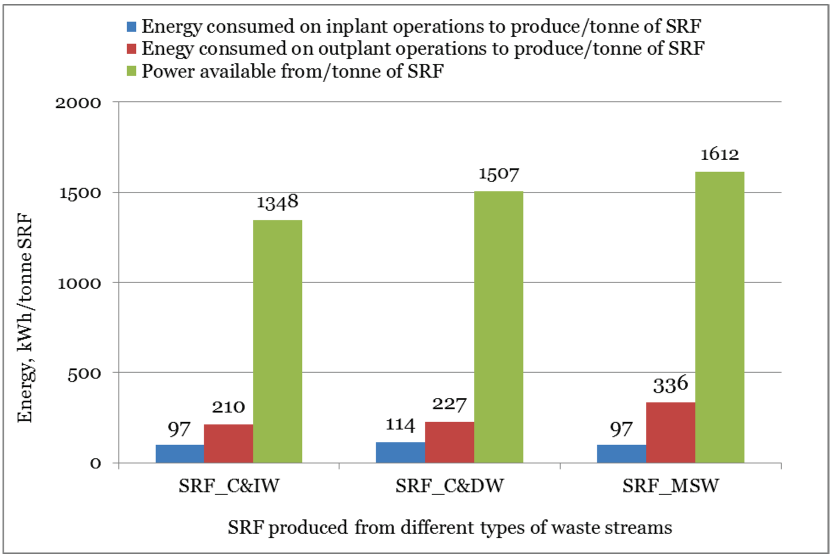


Figure 18. Energy consumed in processing C&IW, C&DW and MSW[a] to produce SRF and the power available from the produced SRF

[a] MSW: Energy waste collected from households

6.4 Identification of source of polluting elements and potentially toxic elements (PTEs) in waste components

The identification of the source of polluting elements and PTEs in various types of waste material (i.e. C&IW, C&DW and MSW) was based on the elemental analysis (see Table 5, Table 8 and Table 11) of their components and the specific elemental load contribution of the components in the waste materials (see Section 3.4, 4.4 5.4). Among the waste components of C&IW, C&DW and MSW, rubber, plastic (hard, especially PVC plastics) and textile (especially synthetic type and flame-retardant textile components) were identified as potential sources of polluting elements and PTEs. The polluting elements and PTEs included chlorine (Cl), lead (Pb), mercury (Hg), cadmium (Cd) and arsenic (As).

In the SRF production, the distribution of rubber, plastic (hard, especially PVC plastics) and textile (especially synthetic type and flame-retardant textile components) from the input waste stream into the output streams needs to be monitored carefully as it played a decisive role in defining the elemental quality of SRF. On the other hand, paper & cardboard, wood and plastic (soft) were identified as containing the least amount of polluting elements and PTEs among the waste components.

Based on the elemental analysis of waste components and their specific elemental load contribution, the distribution/separation of rubber, plastic (hard, especially PVC plastics) and textile (especially synthetic type and flame-retardant textile components) from the input waste stream into the output streams was found to be the most critical in defining the elemental quality of SRF. In this context, the said components are recommended to be directed away from the SRF stream, whereas the maximum recovery of paper & cardboard, wood and plastic (soft) is desired in order to enhance the quality and yield of SRF.

6.5 Mass flow of polluting elements and PTEs in SRF production from C&IW, C&DW and MSW

In this research work, it was observed that the quality and yield of SRF was affected by the type of input waste stream (i.e. C&IW, C&DW and MSW). In SRF production, the characteristics of the input waste stream in terms of composition, moisture content, particle size and shape of waste components was found to have a significant effect on the sorting of waste components in the relevant output stream. The mass flow of polluting elements and PTEs from the input waste stream into the output streams was found to have a direct link with the type and share of waste components distributed in the output streams.

A higher mass flow of polluting elements and PTEs was found in the SRF produced from C&IW in comparison with the SRFs produced from C&D waste and MSW. C&IW processing was found to be complicated because of its high moisture content, and waste components of irregular shape (rolled form of paper and cardboard and textiles) that were large in particle size even after primary shredding. The proper sorting of waste components into the output streams was found to be affected negatively by the said physical properties of the C&IW components. It was noticed that especially the air classifier and NIR sorting units might not perform the sorting of problematic components as designed. A significant mass fraction of combustibles (especially paper and cardboard and wood) was found in the reject material stream that was supposed to be in the SRF stream. In the case of SRF produced from C&D waste, it was found to be less contaminated in terms of polluting elements and PTEs than the SRFs produced from C&IW and MSW. In the case of SRF produced from C&D waste, a high mass fraction of wood in the SRF stream effectively reduced the content of polluting elements (especially chlorine).

6.6 Improving the sorting efficiency of the mechanical processing of waste material

In SRF production from different types of waste materials, based on the results, observations and their comparison, the sorting efficiency of the mechanical processing of waste material can be improved by the following key process-related actions:

- The lightweight components which contained a higher concentration of polluting elements and PTEs (especially chlorine and cadmium) could have been classified by an air classifier (due to their light weight/density) and put into the SRF stream. This issue could be addressed by passing air-classified components through the NIR sorting unit before putting them into the SRF stream. The NIR check could route undesired components away (with negative sorting i.e. sorting the undesired waste components) from the SRF stream.
- Another very important process factor observed which could affect the sorting efficiency of unit operations (especially the air classifier and NIR sorting unit) was balancing the mass flows of the plant through steady feeding of input waste (not trying to feed as much as possible) and adjusting the processes so that the mass flows divided between the processes/unit operations are in line with the designed capacities of the machinery. In other words, too much or sudden peaks of material coming to any of the sorting processes might affect the sorting efficiency of the unit operations. Regular and proper maintenance of plant processes/unit operation equipment (e.g. keeping the air nozzles of the NIR units clean) is also vital to ensure that the machines are working properly and the set-ups are inline.
- Proper/better shredding of input waste stream components in the primary shredder is very helpful in facilitating the unit operations (especially the air classifier and NIR) for better sorting of waste components into the relevant output streams. For example, a considerable mass fraction of combustibles (paper & cardboard and wood etc.) was found in the reject material and heavy fraction streams. The majority of these components had a large particle size (<200 mm, especially wood and textile components) or were heavy in weight/density (paper & cardboard, textile and plastic in bundled/roled form), and were supposed to be in the SRF stream rather than in the reject material.

6.7 Areas of further Advancements in the research

Further innovations and advancements regarding element based waste sorting techniques are needed in SRF production technology to separate the waste components containing undesirable elements; this would be a step forward in transforming the SRF into a mainstream fuel. These techniques could be useful in defining the limit of certain elements' concentration and separating those waste components away from the SRF which contain the polluting and potentially toxic elements beyond the set/desired limit.

Further/advanced automation in the shredding techniques can also be vital in order to optimize the particle size distribution (in terms of particles lengthe and shape) of the waste components. In this context, smart shredder which can sense, for instance the length/diameter of waste components if it is larger than the required one and keeps it within shredding process until it is shredded to desired size in terms of length/diamerete and shape. In the shredding the particle size of the combustible/suiable waste components should not be larger than the desired one so that it gets an appropriate treatment in the separation techniques especially in air classifer and near-infra red (NIR) and get sorted into the relevant output stream. On the other hand, the particle size of the combustible/suitable waste components should be avoided to be in the fines (<15mm) so that these components don't end up in the fine fraction.

Conclusions

In this research work, solid recovered fuel (SRF) was produced from three different types of waste materials through mechanical treatment on industrial scale. The SRF was produced from commercial and industrial waste (C&IW), construction and demolition waste (C&D waste) and municipal solid waste (MSW i.e. energy waste collected from households). The input and output streams produced in SRF production were sampled and treated according to CEN standard methods for SRF. The proximate & ultimate and detailed elemental analysis of the process streams and waste components produced in SRF production were performed. The quality of SRF production was determined through detailed material and energy balances of the SRF production processes. The mass flow of polluting and potentially toxic elements (PTEs) from input to output streams was examined in terms of the elemental balance of SRF production processes. The source of polluting elements and PTEs in the waste materials was identified based on the elemental analysis of the waste components.

In the case of SRF produced from MSW, a higher yield in terms of material and energy recovery was obtained in the form of SRF as compared with SRF produced from C&IW and C&DW. Of the MSW entering the process, 72% was recovered as SRF, equivalent to 86% energy of the input energy content of MSW. Material recovered in the form of SRF from C&IW was 62%, equivalent to 75% of the input energy content of C&IW. Of the C&D waste entering the process, 44% of the material was recovered in the form of SRF, equivalent to 74% of the input energy content of C&D waste. In the SRF produced from MSW, the recovery of paper and cardboard and wood was higher than that recovered in the SRF produced from C&IW and C&D waste. The energy consumed to process waste material to produce SRF was calculated in terms of in-plant and out-plant operations for the three processes separately. The in-plant operations consisted of the unit operations used in the MT plant to sort out the input waste material into the various output streams. The out-plant operations included the logistical means (vehicles/lorries/trucks) to collect waste material from collection points and deliver process products to the customers' premises. For SRF produced from C&IW, C&DW and MSW, the energy consumed in the out-plant operations was 130 kWh, 100 kWh and 242 kWh, respectively, whereas energy consumed in in-plant operations was 60 kWh, 50 kWh and 70 kWh, respectively.

In the case of SRF produced from C&IW, it was found to be comparatively more contaminated with chlorine (Cl), lead (Pb) and mercury (Hg) than the SRFs produced from MSW and C&D waste. In the SRF produced from C&IW, of the input content of chlorine, lead and mercury to the process, 60 %, 58% and 45 % respectively was found in the SRF stream. For SRF produced from C&D waste, the SRF was found to be the least contaminated with chlorine (Cl), lead (Pb) and mercury (Hg) as compared with those produced from C&IW and MSW. In the SRF produced from C&D waste, of the input content of chlorine, lead and mercury to the process, 34 %, 8 % and 30 % respectively was found in the SRF.

In the SRF production, the quality of the SRF was found to be directly linked with the mass and type of waste components distributed/sorted into the output streams. The sorting of waste components in the output streams was found to be significantly affected by their physical properties, i.e. moisture content, particle size and particle shape. For SRF produced from C&IW and C&D waste, a significant mass fraction of combustible components, i.e. paper and cardboard and wood, were found in the reject material stream which was rather supposed to be in the SRF stream. The major fraction of these combustibles had a large particle size (> 200 mm), were highly moist (>25 wt. %) or irregular in shape (some paper and cardboard and textile components in rolled form etc.). The said physical properties of the waste components were attributed to the type of waste material. In MSW, the components were found to possess better physical properties especially in terms of particle size distribution (i.e. not too many components with a large particle size as there were in the C&IW and C&D waste), particle shape (i.e. components of paper and cardboard and textile were not in rolled form etc.) and moisture content (moisture content of MSW was 13.5 wt. %). In SRF production, the performance of air classifiers and near-infrared (NIR) sorting units play a decisive role in defining the quality and yield of SRF.

Among the waste components, rubber, plastic (hard) and textile (synthetic type) were identified as the potential sources of polluting elements and PTEs. In particular, rubber (black/grey in colour) was consistently found to have a higher chlorine content than other waste components. Rubber in C&IW, C&D waste and MSW was measured to contain 8.0 wt. %, 7.6 wt. % and 8.0 wt. % respectively of chlorine. In order to reduce the concentration of polluting and PTEs effectively in SRF, it is recommended to route rubber (especially black/grey in colour), hard plastics (especially PVC plastics) and textile (synthetic type) away from the SRF. On the other hand, paper & cardboard, wood and plastic (soft) were identified as containing the least polluting elements and PTEs and should be recovered in the SRF to effectively reduce the concentration of polluting and PTEs and enhance the yield of SRF.

The SRF produced from various types of waste materials was found to be qualitatively up to the mark as per standards in terms of economic (net calorific value), technical (chlorine content) and environmental (mercury content) parameters. The quality of SRF was found to be within the range of class 1 – class 3, as per CEN standards for SRF. The extent of variation was relatively higher for the concertation of chlorine, lead and cadmium in the SRF as compared to that of arsenic and mercury. The extent of variation in the said parameters could be a cause of concern for the user of SRF as a mainstream fuel, especially in power production plants. The production of SRF from waste material (especially which is complicated/not feasible to recycle) is a very good and competitive option for waste management, as it recovers value in terms of energy and recyclables from waste and leaves a comparatively very small fraction of waste material to be landfilled.

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PAPER I

Mass, energy and material balances of SRF production process. Part 1: SRF produced from commercial and industrial waste

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Mass, energy and material balances of SRF production process. Part 1: SRF produced from commercial and industrial waste

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ABSTRACT

This paper presents the mass, energy and material balances of a solid recovered fuel (SRF) production process. The SRF is produced from commercial and industrial waste (C&IW) through mechanical treatment (MT). In this work various streams of material produced in SRF production process are analyzed for their proximate and ultimate analysis. Based on this analysis and composition of process streams their mass, energy and material balances are established for SRF production process. Here mass balance describes the overall mass flow of input waste material in the various output streams, whereas material balance describes the mass flow of components of input waste stream (such as paper and cardboard, wood, plastic (soft), plastic (hard), textile and rubber) in the various output streams of SRF production process. A commercial scale experimental campaign was conducted on an MT waste sorting plant to produce SRF from C&IW. All the process streams (input and output) produced in this MT plant were sampled and treated according to the CEN standard methods for SRF: EN 15442 and EN 15443. The results from the mass balance of SRF production process showed that of the total input C&IW material to MT waste sorting plant, 62% was recovered in the form of SRF, 4% as ferrous metal, 1% as non-ferrous metal and 21% was sorted out as reject material, 11.6% as fine fraction, and 0.4% as heavy fraction. The energy flow balance in various process streams of this SRF production process showed that of the total input energy content of C&IW to MT plant, 75% energy was recovered in the form of SRF, 20% belonged to the reject material stream and rest 5% belonged with the streams of fine fraction and heavy fraction. In the material balances, mass fractions of plastic (soft), plastic (hard), paper and cardboard and wood recovered in the SRF stream were 88%, 70%, 72% and 60% respectively of their input masses to MT plant. A high mass fraction of plastic (PVC), rubber material and non-combustibles (such as stone/rock and glass particles), was found in the reject material stream.

1. Introduction

The waste hierarchy (European Commission, 2008) mentions clearly that recycling of material is generally preferable to energy recovery however, for economic, logistical and environmental reasons it is not possible to recycle 100% of the theoretically recyclable material in the municipal solid waste (MSW). When recycling of waste material is not feasible, such material should be treated for energy recovery. The Waste Framework Directive also notes that, if supported by life cycle thinking, options lower down the hierarchy may be adopted in some circumstances if this provides a better environmental solution. This reduces the disposing of material for landfilling and also provides the replacement of fossil fuel with a corresponding reduction in energy related greenhouse gas emissions (Burnley et al., 2011).

In selective waste collection system, recyclable material can be used directly for recycling but in case of mixed waste collection there is a high fraction of waste material which is complicated or may not be feasible to sort out for recycling purposes. All the waste material cannot be recycled and moreover, the material recycling chains always generate high amounts of residues, in some cases having high heating values (Garg et al., 2009; Arena and Gregoria, 2014). It has been recognized that in a fully sustainable waste management system no single process is suitable for all the waste streams (McDougall et al., 2001; Brunner, 2009; Bosmans et al., 2013; Ionescu et al., 2013; Santibañez-Aguilar et al., 2013; Menikpura et al., 2013).

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The non-hazardous waste fractions can be turned into solid recovered fuel (SRF) to be utilized in sustainable energy recovery processes. SRF is prepared from non-hazardous waste to be utilized for energy recovery in incineration/co-incineration plants and meeting the classification and specifications requirements laid down in CEN standards (EN 15359; Rada and Andreottola, 2012; Velis et al., 2011). By 'prepared' here means processed, homogenized and up-graded to a quality that can be traded amongst producers and users. In Europe, SRF is produced from various types of waste streams such as household waste (HHW), commercial and industrial waste (C&IW), construction and demolition waste (C&DW) and from some selected streams of waste material (Velis et al., 2013; Rada and Ragazzi, 2014; Lorber et al., 2012).

In Europe, mechanical treatment (MT) or mechanical biological treatment (MBT) (Ragazzi and Rada, 2012; Velis et al., 2011; Ionescu et al., 2013; Rada and Ragazzi, 2014) plants are used to produce SRF. In MT plants various unit operations/sorting techniques are used (such as shredding, screening, magnetic and eddy current separation, pneumatic separation, optical sorting and near-infrared (NIR) sorting) for the sorting of input waste material to produce SRF.

Commercial and industrial waste (C&IW) has a significant potential in terms of energy fuel and must not be overlooked while considering the future fuels to be used for energy generation (Lupa et al., 2011). C&IW is a solid waste generated by commercial and industrial sector (shopping centres, offices, warehouses and logistics, manufacturing organizations and retail outlets, etc.) and institutions (educational institutions, hospitals and government offices, etc.) excluding construction and demolition waste, household waste and clinical waste. A significant amount of C&IW comprises of components (such as paper & cardboard and plastics) having high heating values.

In Finland, waste-to-energy technology is focused on co-firing in combined heat and power (CHP) production, mainly through fluidized bed combustion and gasification technology. In Finland at the moment, the fraction of C&IW which is relatively complicated or not feasible to sort out for recycling purposes and partly residues of waste material generates from C&IW recycling chains having high heating value is managed through MT plants to produce SRF. This SRF is used as a fuel/co-fuel in the cement kilns and fluidized bed boilers of some dedicated combustion and gasification power plants. The quality of SRF is based on an efficient and extensive source separation of waste material and recovered fuel production technology (Wilén et al., 2002).

The objective of this paper is to analyse the material flows and their characteristics in the various streams of material produced in SRF production process produced from C&IW. In this work, various streams of material produced in MT based SRF production plant are analyzed in terms of their proximate and ultimate analysis. The composition (break down by types of contained material such as paper and cardboard, wood, plastic, textile and rubber) of process streams is determined through manual sorting. Based on these analysis of process streams their mass, energy and material balances are established for this SRF production process. In order to establish these balances a commercial scale experimental campaign was conducted to produce SRF from C&IW. A batch of 79 tons of C&IW was collected from the Metropolitan area of Helsinki region which was transported to an MT based waste sorting plant to produce SRF. Based on unit operations and sorting techniques used in the MT plant, the input waste stream (i.e. C&IW) was further divided into various output streams such as SRF, ferrous metal, non-ferrous metal, reject material, fine fraction and heavy fraction. All the process streams (input and output) were sampled and treated according to the CEN standard methods for SRF (EN 15442; EN 15443). The balances are presented here in the form of sankey diagrams. Sankey diagrams are suitable way to visualize the mass and energy flow balances in which the width of arrow is proportional to the quantity of flow.

2. Materials and methods

2.1. Process description

Various sorting techniques were used in MT plant to produce SRF from C&IW. These techniques included primary shredding, screening, magnetic and eddy current separation, air classification, near-infrared (NIR) sorting and secondary shredding. Based on these unit operations the input waste material (i.e. C&IW) was further divided into various output material streams as shown in Fig. 1.

Sorting of the input waste stream into various output streams was based on particle size distribution, weight/density, ferrous/non-ferrous metal and near-infrared (NIR)/specific spectral properties of waste components. The purpose of using various sorting techniques in this MT plant is to selectively separate the impurities (such as inert material, metals and highly chlorinated/pollutant waste components) from the input waste material into small streams to produce a high yield of quality controlled SRF stream. The function of various sorting techniques used in this MT plant to produce SRF is described below.

2.1.1. Primary shredding

In the primary shredding, input waste stream (i.e. C&IW) was shredded to a nominal top size (D_{95} 150 mm). Primary shredding was useful in order to homogenise, deal with the large and hard particles and to open the closed plastic bags of input waste material.

2.1.2. Screening

Screening was very next unit operation used after primary shredding of input waste stream. Jigging and drum screens were used in screening section to separate waste material based on particle size distribution such as material with particle size <15 mm was separated as fine fraction, material with particle size >300 mm was separated and put again in the primary shredder, and material with particle size in between these two streams was treated in further unit operations.

2.1.3. Magnetic and eddy current separation

Components of ferrous and non-ferrous metals of input waste stream were separated in magnetic and eddy current separators respectively. In order to recover maximum amount of metals from input waste stream, several magnetic and eddy current separators were used on various locations in the process.

2.1.4. Air classification

Light weight components (such as paper and cardboard, plastics, textile, foam and wood) from input waste material were separated in the wind shifter and put into the stream of SRF. In wind shifter air flows in cross direction of falling material and separates light weight components from heavy and middle weight components.

2.1.5. Near-infrared (NIR) sorting

The role of near-infrared (NIR) sorting unit here was to separate the combustibles (such as paper and cardboard, wood and non-PVC plastic) from input waste material and to put them into the SRF stream. In this MT process, NIR sensor was set on positive sorting and it separated the combustible components of waste material and rest of material (i.e. inert, PVC-plastic and other highly chlorinated components) ended up in the reject material

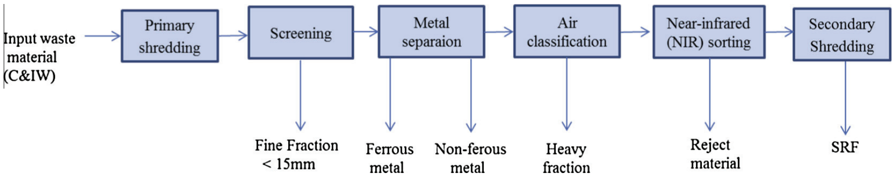

Fig. 1. Simplified MT process to produce SRF from C&IW.

stream. Combustible components of input waste stream which were not separated in air classification sorting (i.e. components medium in weight/density, etc.) passed further through an automated sorting unit based on near-infrared (NIR) technology. The sorting of NIR sensor was based on the NIR/specific spectral properties of components of waste material. The near-infrared (NIR) based sorting technique and principle are described in details (Reich, 2005).

2.2. Process streams

The process streams involved in MT based SRF production plant and their nominal top sizes (D_{95}) were;

- *Input stream:* Commercial & industrial waste (D_{95} 150 mm after primary shredding).
- *Output streams:* SRF (D_{95} 75 mm), fine fraction (D_{95} 10 mm), reject (D_{95} 85 mm), reject (D_{95} 120 mm), heavy fraction (D_{95} 150 mm), ferrous metal (D_{95} 150 mm) and non-ferrous metal (D_{95} 150 mm).

There were two streams of reject material, separated based on their particle size distribution i.e. reject (D_{95} 85 mm) and reject (D_{95} 120 mm).

2.3. Sampling methodology

In order to take the representative samples of input and output process streams form SRF production plant and to prepare their samples for laboratory analysis, their sampling and sample preparation were performed according to the CEN standard methods for SRF: EN 15442 and EN 15443. These methods were applied on two stages,

- Sampling of process streams from SRF production plant.
- Preparation of process streams' samples for laboratory analysis samples.

Sampling of the input and output streams from SRF production plant was done according to EN 15442 and their preparation for the laboratory analysis samples was done according to EN 15443. As per EN 15442, increment size of the process streams was 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 from SRF production plant. Increment size is the portion of material extracted in a single operation. Increments of respective streams were combined together to form their combined samples. The increment extracted in the first stage of sampling is termed as primary sample and primary samples (i.e. increments) were combined together to form a combined sample (ISO 18283) of process stream. Due to comparatively homogeneous nature of streams such as ferrous metal, non-ferrous metal and heavy fraction, only 4 increments of each of these stream were taken and combined together to form their respective combined samples. Particle sizes and bulk densities of process streams were different from each other and therefore the increment sizes as well.

2.3.1. Sampling of process streams from SRF production plant

Methods applied for the sampling of input and output streams from SRF production plant were,

- Static lot method.
- Manual drop flow method.

According to EN 15442, a lot that is not in motion during its sampling, or transported by a conveyor or alternative transport system is a static lot. Static lot method was used to sample the streams of C&IW (input waste stream), SRF, fine fraction, heavy fraction, ferrous metal and non-ferrous metal. While, manual drop flow method was used to sample the streams of reject (D_{95} 85 mm) and reject (D_{95} 120 mm). The use of sampling method was based on the operational situation of process streams and SRF production plant. In static lot method each of the stream was sampled in such a way that the lot of material was divided dimensionally into several equal parts and 24 increments were taken randomly from these parts for each stream. These 24 increments of the respective stream were combined together to make combined sample for each stream. For streams of ferrous metal, non-ferrous metal and heavy fraction, only 4 increments of each of these stream were taken and combined together to make their respective combined samples. These streams were comparatively homogeneous in terms of their components (see chapter 4) and, therefore it was not realized to take more than 4 increments for each of these stream. Sampling of the reject (D_{95} 85 mm) and reject (D_{95} 120 mm) streams was done by using manual drop flow method. The material of reject (D_{95} 85 mm) and reject (D_{95} 120 mm) streams was dropping down from the conveyor belt and increments were collected manually by putting the sampling container under the conveyor belt after equal interval of time. Time interval for this method was 30 min which was based on collecting 24 increments in total process time. These 24 increments of each reject stream were combined together to form their respective combined samples. The sampling quantities of process streams, their top nominal sizes, increment sizes and combined samples are given in Table 1.

2.3.2. Sample preparation of process streams for laboratory analysis

Sample preparation of the process streams for their laboratory analysis was done according to EN 15443. The purpose here was to reduce the original size (mass) of combined samples of process streams (see Table 1) to a laboratory test portion size (mass) by not changing its original composition during each step of sample preparation. Sample preparation of the combined samples of process streams for their laboratory analysis was done in two stages; sample preparation before sending samples to laboratory and sample preparation in the laboratory.

Table 1
Sampling of process streams from SRF production plant.

Process stream	Nominal top size D_{95} (mm)	Increment size (kg)	Combined sample[a] (kg)
C&IW (input stream)	150	20	480
SRF	75	2.5	60
Reject	85	5.0	120
Reject	120	10	240
Fine fraction	10	1.0	24
Heavy fraction	150	20	80
Ferrous metal	150	20	80
Non-ferrous metal	150	20	80

[a] Combined sample is sum of 24 increments for C&IW, SRF, reject (D_{95} 85 mm), reject (D_{95} 120 mm) and fine fraction and sum of 4 increments for heavy fraction, ferrous metal and non-ferrous metal.

2.3.2.1. Sample preparation before sending samples to laboratory. As per EN 15443 two basic methods were applied at every step of sample preparation,

- Particle size reduction.
- Sample division (mass reduction).

Aim of particle size reduction was to reduce the nominal top size (D_{95}) of combined samples of process streams to reduce the sample mass size without losing the representativeness of original samples. Particle size reduction of combined samples of process streams was done by using shredder and sieves of various mesh sizes. Nominal top size (D_{95}) of each stream was reduced to 30 mm. Stream of fine fraction was not further shredded as it was already having D_{95} of <15 mm. After particle size reduction of process streams to D_{95} of 30 mm, next step was to reduce their sample size in terms of mass. Manual increment division method was applied to reduce the sample size (mass) of shredded (30 mm) combined samples of process streams. Metals in each stream were excluded in sample preparation for the laboratory analysis. In manual increment division method, each shredded stream (D_{95} 30 mm and D_{95} 15 mm for fine fraction) was mixed well and spread on a thick sheet into a rectangular form. This (rectangular shape sample) was equally divided into 20 sections and increments were taken from each section randomly with sampling scoop from top to bottom. As a result of manual increment division method the mass of each of process stream i.e. C&IW (input waste stream), SRF, reject (D_{95} 85 mm), reject (D_{95} 120 mm) and fine fraction was reduced to 15 kg and that of fine fraction (D_{95} 10 mm) to 5 kg and sent to laboratory for their further sample preparation and analysis.

2.3.2.2. Sample preparation in laboratory. Set of apparatus used in the laboratory for further sample preparation of process streams' samples included cutting mill, crushing mill, grinding mill and riffle divider. This set of apparatus was used in series to reduce the nominal top size (D_{95}) and mass size of samples at each stage. Cutting, crushing and grinding mills were used to further reduce nominal top size (D_{95}) of samples from 30 mm to 20 mm, 10 mm and 0.5 mm respectively. D_{95} of fine fraction was already10 mm and, therefore sample preparation for this stream was started from grinding mill. Sample size (mass) of samples was reduced at every stage by using riffle divider. By using this set of apparatus in the laboratory, top nominal size (D_{95}) and mass size of samples of each stream were reduced to 0.5 mm and 0.5–5 g respectively as final laboratory test analysis portion. The procedure of sample preparation for laboratory analysis of process streams in the laboratory is illustrated in Fig. 2.

Final samples of process streams having D_{95} of 0.5 mm and mass of 0.5–5 g were analyzed in the laboratory for their proximate and ultimate analysis. The reject streams i.e. reject (D_{95} 85 mm) and reject (D_{95} 120 mm) were combined together into one sample stream as reject material for laboratory analysis.

2.3.2.3. Sample preparation for components of C&IW. The components of C&IW (such as paper and cardboard, plastic (soft), plastic (hard), wood, textile, rubber, foam and fines) were obtained by manual sorting of input process stream into it's components. Methods applied for the sample preparation of input waste's components for their laboratory analysis were same as for process streams (described in Sections 2.3.2.1. to 2.3.2.2).

3. Results and discussions

Samples of the process streams analyzed in laboratory were: C&IW (input waste material), SRF, reject and fine fraction. The components of C&IW analyzed in laboratory were: paper and cardboard, plastic (soft), plastic (hard), wood, textile, rubber and foam material. Standard methods used for the laboratory analysis of process streams and components of C&IW are listed in Table 2. Stream of heavy fraction was not analyzed in the laboratory as its mass fraction was relatively very less as compared with the other streams (see Section 3.1.1.) and in its composition the major components were inert and metals. Metals were not included in the laboratory analysis of process streams.

A high heating value (NCV, dry) of SRF stream was measured in the laboratory as 25.0 MJ/kg. This high heating value of SRF was due to the high mass fraction of plastics in it. As this SRF was produced from C&IW which contained high mass fraction of components with high heating values (such as paper and cardboard, plastic and textile).

Plastics are the main components in the fuel, leading to higher calorific values (Susanne et al., 2004). High heating values (i.e. LHV 23.56 MJ/kg, dry) of SRF has been reported in literature (Vainikka et al., 2011). Net calorific value (NCV, a.r.) of class 1 SRFs is reported as ≧25 MJ/kg (EN 15443). Moisture content of the SRF was measured in the laboratory as 25.0 wt.%. This is a high value of moisture content of this SRF stream considering the fact that there is a large proportion of paper and cardboard and plastics in it. The primary shredding of the input waste material might have caused the cross contamination of moisture content to paper and cardboard and plastic components from other components with high moisture content. High values of moisture content of SRF have been reported in literature such as 28.1 wt.% (Agraniotis et al., 2010). High moisture content measured for the streams (input and output) might be due to the seasonal effect, as this experimental campaign was conducted in winter time of the year in Finland. Ash content (at 550 °C) of SRF was measured as 12.5 wt.%. In the components' analysis, ash content of paper and cardboard and fines were measured as 13.5 wt.% and 54.4 wt.% respectively. High mass fraction of paper and cardboard and incombustible impurities in the SRF increase the ash content (Velis et al., 2011).

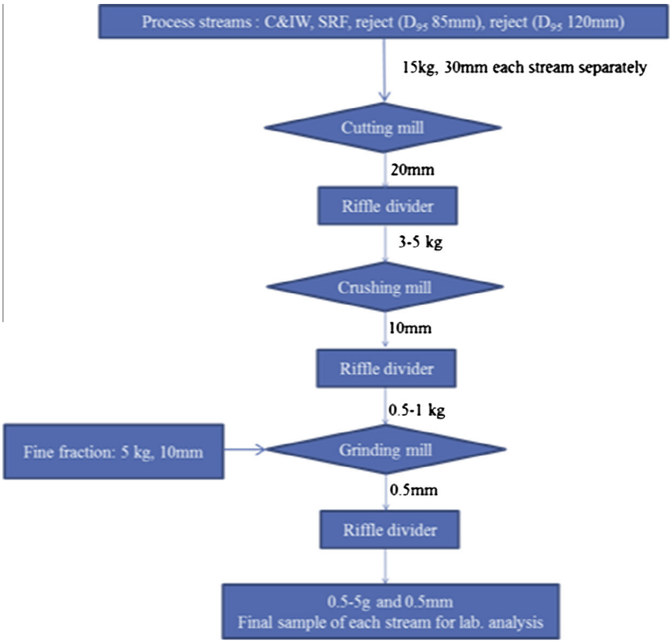

Fig. 2. Procedure of sample preparation of process streams in laboratory.

Table 2
Standard methods used for laboratory analysis of process streams produced in SRF production plant and components of input waste stream.

Parameter	Standard methods
Moisture content	E N 14774-2, CEN/TS 15414-2, ISO 589
Ash content (550 °C)	EN 14775, EN 15403
Heating value	EN 14918, EN 15400, ISO 1928
C, H, N, ($O_{calculated}$)	EN 15104, EN 15407, ISO 29541
S	EN 15289, ASTM D 4239 (mod).

Heating value of the reject stream produced in this SRF production process was measured in laboratory as 16.6 MJ/kg (NCV, dry). This high heating value of reject stream was due to the presence of components (such as PVC-plastic and rubber material) in it. Material ended up in the reject stream after being passed from near-infrared (NIR) sorting unit, where combustibles were sorted out into the SRF stream and non-combustibles (inert material) and highly chlorinated material (such as PVC-plastic and rubber) to the reject stream.

Proximate and ultimate analysis of the process streams of this SRF production plant produced from C&IW and components of C&IW are given in Table 3. The laboratory analysis values (given in Table 3) were adjusted for the metals as their quantities in each process stream were known from the composition of streams and energy wise metals were considered as inert (i.e. zero heating value) (Biffaward programme, 2003). The composition of process streams is described (see chapter 4).

3.1. Mass and energy flows balances in process streams of SRF production process

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

3.1.1. Mass flow balance in process streams of SRF production process

Mass flow balance in process streams of SRF production process was established for a batch of 79 tons of C&IW fed to MT waste sorting plant to produce SRF. In order to make the mass flow balance, all the output streams produced in SRF production plant were weighed. All the input waste material (i.e. C&IW) was recovered in the form of output streams with a negligible amount of difference (i.e. sum of the mass of output streams was 78.86 tons). The mass flow balance in process streams of this SRF production process produced from C&IW is shown in Fig. 3 in the form of a sankey diagram. This mass balance was based on the weight of input waste stream.

Use of output streams from this MT based SRF production plant is such that: the SRF is process product which is used for energy recovery in the dedicated CHP gasification and combustion plants, metals (ferrous/non-ferrous) are recycled and the streams of reject material, fine fraction and heavy fraction (based on their composition) are utilized partly for energy recovery, environmental construction (landfill construction) and disposed to landfill.

3.1.2. Energy flow balance in process streams of SRF production process

Energy flow balance in the process streams of SRF production process was based on the law of energy conservation; the input energy balance was calculated from sum of the energy content of output streams. This was facilitated by the fact that the input waste material (i.e. C&IW) was not subjected to any material transformation and moreover, the process does not store any material in the system and only does mechanical separation of material.

Heating values (NCV, MJ/kg) of the process streams were multiplied by their respective total masses to calculate their total energy

Table 3
Laboratory analysis results of process streams and components of C&IW taken from SRF production plant produced from C&IW.

Process stream	Moisture content (wt.%)	Ash content 550 °C (wt.%)	C (wt.%)	H (wt.%)	N (wt.%)	S (wt.%)	$O_{calc.}$ (wt.%)	NCV[a] MJ/kg (a.r.)[c]	GCV[b] MJ/kg (d.)[d]	NCV[a] MJ/kg (d.)[d]
C&IW	26.5	16.6	48.0	7.0	0.6	0.2	18.0	13.0	19.8	18.5
SRF	25.0	12.5	57.4	8.0	0.5	0.3	17.8	18.0	26.6	25.0
Reject material	26.0	23.0	41.0	5.8	1.0	0.3	20.8	11.6	18.8	16.6
Fine fraction	44.5	48.0	29.6	4.0	1.2	0.8	16.0	5.5	12.6	12.0
Components of commercial and industrial waste (C&IW)										
Paper & cardboard	n.a.	13.0	42.5	5.6	0.4	0.1	38.0	n.a.	17.3	16.0
Plastic (soft)[e]	n.a.	10.3	74.6	12.0	0.3	0.2	2.3	n.a.	39.5	37.0
Plastic (hard)[e]	n.a.	6.0	74.4	11.4	0.3	0.1	5.0	n.a.	37.4	35.0
Textile	n.a.	10.4	57.4	7.6	1.8	0.24	21.3	n.a.	26.5	24.8
Wood	n.a.	1.6	49.0	6.2	0.8	<0.02	42.2	n.a.	20.0	18.6
Rubber	n.a.	23.0	48.0	5.2	1.0	0.5	14.3	n.a.	21.0	20.0
Foam	n.a.	5.0	62.5	8.4	4.0	0.1	19.8	n.a.	29.0	27.3
Fines	n.a.	54.4	26.8	3.5	1.3	1.0	22.6	n.a.	10.6	9.8

[a] NCV net calorific value.
[b] GCV gross calorific value.
[c] (a.r.) as received basis of material.
[d] (d.) dry basis of material.
[e] Plastic (soft) and plastic (hard) were separated on the basis of their physical softness and hardness. n.a. not available.

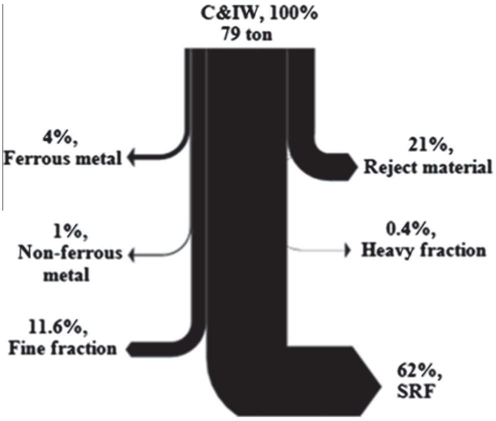

Fig. 3. Mass flow balance in process streams of SRF production process: SRF produced from C&IW (wet basis).

content. This was done for both wet and dry basis of material. Masses of the process streams were taken from mass flow balance in process streams of SRF production process (Section 3.1.1.) and their moisture content and hating values were taken from the laboratory analysis of process streams (Table 3). Energy content of heavy fraction stream was calculated from its composition and heating values of the components (Table 3). The difference found in the measured and calculated values of the input energy content is calculated as an error value. In case of energy balance made on wet basis the calculated value of the input energy was 10% lesser than the measured value. While in case of energy balance on dry basis the calculated value of the input energy was 9% higher than its measured value. Energy flow balances in process streams of this SRF production process produced from C&IW on wet and dry basis are shown in Fig. 4 in the form of sankey diagrams.

The deviation of calculated error values of energy flow balances for wet and dry basis was calculated high. This difference was due to the high moisture content of process streams (especially C&IW and SRF streams). Energy recovered by this MT based SRF production plant in the form of SRF was 75% and 78% of total input energy content for wet and dry basis of material respectively. Energy belonged with the ferrous metal and nonferrous metal streams was due to very minor amount of combustibles (such as paper and cardboard, plastic and foam and wood) in these streams and not due to metals as energy value of metal was taken as zero (Biffaward programme, 2003).

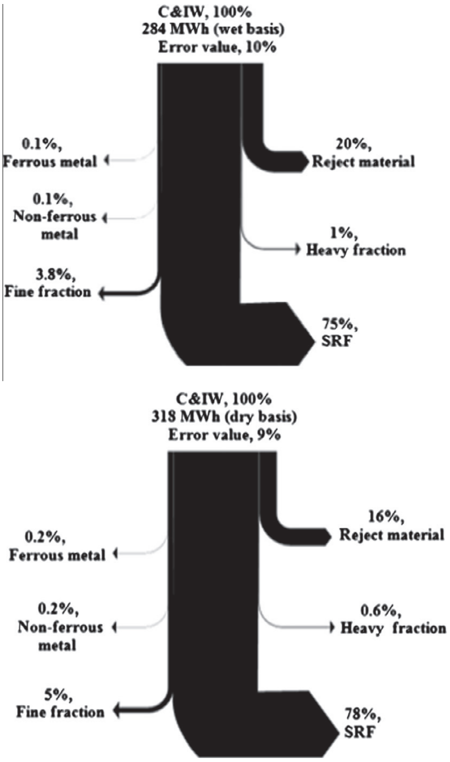

Fig. 4. Energy flow balances in process streams of SRF production process: SRF produced from C&IW.

Energy was also partly recovered from other streams such as reject material and fine fraction. But the fraction of energy recovered from these streams was comparatively smaller and, moreover being reject material and fine fraction these streams could not be utilized directly for energy recovery purposes but after some further treatment.

3.2. Energy consumed in processing C&IW to produce SRF

Amount of energy consumed in processing the batch of 79 tons of C&IW on MT waste sorting plant to produce SRF was divided into two operations:

- Inplant operations.
- Outplant operations.

Inplant operations comprised of unit operations and sorting techniques used in MT plant to produce SRF from this batch of C&IW. These unit operations included; primary shredding, screening, magnetic and eddy current separation, wind shifters, near-infrared (NIR) units, secondary shredding, conveyor belts, material handling machinery (such as wheel loaders and excavators) and dust extraction system.

Outplant operations comprised of logistics (i.e. vehicles transportation) involved in collecting the C&IW from its collection points and to transport it to MT plant and it also included the transportation of output streams (such as SRF, metals, rejects, fine and heavy fraction) to customer's premises. Energy consumption values (in kW h) for the inplant and outplant operations were measured/calculated and provided by the plant authorities. Shredding was the most energy consuming unit operation as compared with the other unit operations in this MT based SRF production plant. The consumption of energy for logistical operations was calculated in terms of diesel consumption for trucks/lories used and was converted to kW h values. For this process, energy consumed by the inplant and outplant operations is given in Table 4.

Energy consumed on the outplant operations depended upon the distance to cover in logistics (i.e. how far were the waste collecting points from the treatment plant and customer's premises to deliver the output streams). For this specific process the average route distance covered to collect the C&IW from various collection points (waste bins and compactors) was 167 km and to deliver the output stream (i.e. SRF) to customer's premises was 120 km. Energy consumed on the outplant operations (logistical operations) was approximately 2.2 times of the energy consumed on the inplant operations (sorting techniques/unit operations used in MT waste sorting plant to produce SRF from C&IW). The studies (such as primary energy used to generate the power consumed on this process, this power was generated from which fuel and description of plant used to generate this power) are beyond the scope of this research.

Table 4
Consumption of energy to process C&IW on MT waste sorting plant to produce SRF.

Process	Unit	Energy consumption/*t* of input waste material
Inplant operations	kW h	60
Outplant operations	kW h	130

4. Composition of process streams

By composition of process streams means their breakdown by types of contained material (such as paper and cardboard, wood, plastic and textile etc.). In order to determine the composition of process streams their respective combined samples (see Table 1) were manually sorted out into their components. The composition of process streams was based on wet mass basis of material.

In Finland, source separation system is based on sorting of commercial waste into 2–6 fractions. The source separation of waste material plays a vital role of good material recovery for recycling and production of high quality SRF. Commercial waste mainly contains polyethylene plastic, paper and cardboard and wood (Wilén et al., 2002). The components (such as food waste, sanitary waste and green waste) are excluded from commercial and industrial waste. This is a practise especially in the major cities.

The streams of C&IW (input waste) and SRF produced from it were found to be enriched with paper and cardboard and plastic. C&IW contained 31.0 wt.% of paper and cardboard, 17.0 wt.% of plastic (soft) and 14.6 wt.% of plastic (hard) in its composition. The SRF produced from C&IW contained 35.6 wt.% of paper and cardboard as a major fraction in its composition. Paper and card is reported as a dominant fraction of SRF (Velis et al., 2011).The mass fraction of plastic (soft) was found to be higher than that of plastic (hard) in the SRF stream. The mass fraction of plastic (soft), plastic (hard) and textile in this SRF stream was 24.0%, 16% and 8.5% respectively. SRF is a high calorific value material (containing paper, plastic, textile and wood) (Garg et al., 2009).The reject stream was found to be heterogeneous in terms of its composition. The reject stream was mainly consisted of non-combustibles/inert material (such as stone, glass particles and fines) along with noticeable mass fraction of plastic (PVC-plastic), rubber material, paper and cardboard and wood. Components of paper and cardboard and wood found in the reject stream, most of them were large in particle size (>200 mm), irregular in shape or heavy in weight (i.e. very moist or paper in bundle form, etc.). In ferrous metal stream mass fraction of metals was 92 wt.% and in non-ferrous metal stream mass fraction of metals was 88 wt.%. Some light weight components (such as paper and cardboard, foam, textile, wood having iron/steel nails and

Table 5
Composition of various process streams produced in MT waste sorting plant to produce SRF from C&IW (wet basis).

Component	C&IW (wt.%)	SRF (wt.%)	Reject material (wt.%)	Ferrous metal (wt.%)	Non-ferrous metal (wt.%)	Heavy fraction (wt.%)	Fine fraction (wt.%)
Paper and cardboard	31.0	35.6	12.4	1.0	2.6	2.0	4.5
Plastic (hard)	14.6	16.5	14.0	1.2	2.8	3.5	2.6
Plastic (soft)	17.0	24.0	4.7	0.6	2.0	n.a.	5.8
Textile	9.0	8.5	9.2	1.4	1.4	n.a.	3.8
Wood	6.8	6.4	4.0	3.6	0.4	4.6	5.6
Rubber	2.6	1.0	6.8	0.2	0.8	4.5	0.8
Metal	6.4	0.8	3.2	92.0	88.0	16.0	0.8
Foam	1.0	1.2	0.2	n.a	0.6	n.a.	4.5
Glass	3.6	n.a.	10.0	n.a	1.4	1.4	16.8
Stone	3.0	n.a.	18.5	n.a	n.a	66.2	28.2
Fines	5.0	6.0	17.0	n.a	n.a	1.8	26.6

rubber) were also found in the ferrous/non-ferrous metal streams in a very small fraction. These light weight components might be in contact (in between or on top, etc.) with the metals during magnetic and eddy current separation process. The composition of process streams produced in this MT based SRF production plant produced from C&IW is given in Table 5.

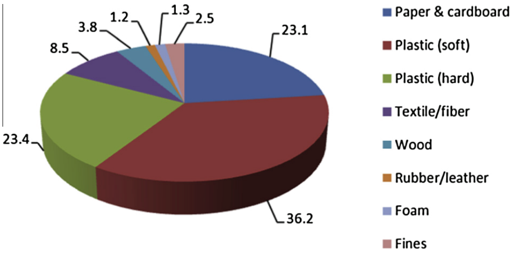

Fig. 5. Energy based composition of SRF produced from C&IW.

Stream of heavy fraction consisted of mainly heavy particles of stones/rocks and metals and stream of fine fraction was found to be mainly consisted of shredded particles of stone/rocks, and glass and small fraction of combustibles (such as paper and cardboard, plastic, wood, textile and foam). In the sorting process these waste components were shredded to small particle size (<15 mm) in the primary shredding of input waste material and screened out as fine fraction. The stream of SRF got enriched in paper and cardboard and plastics (soft and hard) as compared with the input waste stream (i.e. C&IW). Paper and cardboard and plastic (soft, hard) together formed 76.0 wt.% (wet basis) of this SRF stream.

Energy based composition of the SRF stream was calculated from its composition (on mass basis) and net calorific values of components (see Table 2). The energy based composition of SRF produced from C&IW in this process is given in Fig. 5.

Major portion of energy in this SRF produced from C&IW contained by the plastic (soft), plastic (hard) and paper and cardboard respectively. Plastics (soft and hard) and paper and cardboard in the SRF stream contained 59.6% and 23.1% of the total energy content of SRF. Plastic (soft) contained more energy fraction than that of plastic (hard) in this SRF produced from C&IW.

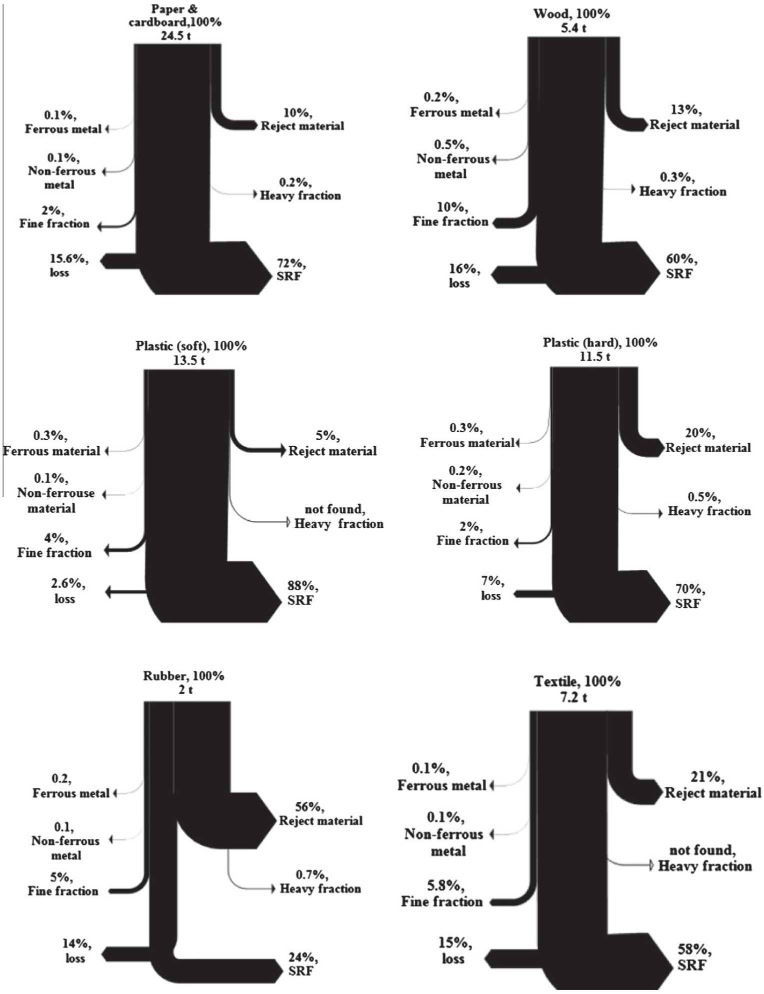

Fig. 6. Materials mass flow balances of components of input waste material in output streams of MT based SRF production process produced from C&IW (wet basis).

5. Material balances

Material balances included the mass flow balances of components of input waste material (i.e. C&IW) in various output streams of SRF production plant. These material balances were made on wet basis for components: paper and cardboard, wood, plastic (soft), plastic (hard), textile and rubber. The flow of components of input waste stream into various output streams was based on the unit operations used in MT plant to produce SRF. Operators manufacturing SRF with a specified quality need to understand the materials flow of waste components (paper, plastics, wood, etc.) through their facilities to optimize plant configurations and produce SRF with predictable properties (calorific value, ash content, and chlorine content for end users (Velis et al., 2013).

In order to make the materials mass flow balances, quantities of input waste's components in all the process streams (input and output) were calculated from composition of process streams (see chapter 4) and total masses of process streams (see Section 3.1.1.). The materials mass flow balances of paper and cardboard, wood, plastic (soft), plastic (hard), textile and rubber are shown in Fig. 6 by using sankey diagrams. These material balances were based on the weight of waste's component in the input waste stream. The loss value given here was the difference of quantity (mass) between calculated mass of component in the input material stream and the sum of the mass of same component in the output streams.

Some considerable amount of combustibles (such as paper and cardboard and wood) were found in the reject stream which were not supposed to be there, but in the SRF stream. Being biogenic by definition and not having significant impact on ash content, increasing mass fraction of paper and card in the SRF is reported in literature (Velis et al., 2011). Mass fraction of paper and cardboard, wood and textile found in the reject streams was 10%, 13% and 21% respectively of their total input masses to MT plant to produce SRF. It was observed that most of the components of paper and cardboard, wood and textile found in the reject material stream were highly moist, large in particle size (>200 mm) or irregular in shape. Components of textile found in the reject stream were mainly synthetic type of textile (not fibrous textile). Material ended up in the reject stream was coming after being passed from wind shifter and near-infrared (NIR) sorting units. In this MT process the NIR sorting unit was set on positive sorting. By positive sorting here means to pick up the combustibles (such as paper and cardboard, non-PVC plastics and wood) from waste material based on their NIR/specific spectral properties and put them into the SRF stream. Being very moist, large in particle size (>200 mm) or irregular in their shape for these components (such as paper and cardboard and wood) in the reject stream might be the reason for not being picked up by these unit operations (such as wind shifter and NIR sorting unit). In order to optimize the sorting effect weight/density, shape and particle size distribution of the particles play an important role (Susanne et al., 2004). Components such as wood, paper and cardboard and partly textiles found in the reject stream are suitable as fuel material to increase the yield of SRF stream if a drying step is included in the sorting process and particle size distribution of the components is optimized in the shredding. The native-organic and paper components have an acceptable calorific value (LHV about 15,000 kJ/kg) (Kost, 2001).

Plastic (soft) was recovered in the SRF stream in highest mass fraction as compared with the other components of input waste stream. The mass fraction of plastic (soft) recovered in the SRF stream was 88% of its input mass to MT plant. Being light in weight plastic (soft) are relatively easier to get separated from the waste components by unit operation such as wind shifter and carried into the SRF stream. The mass fraction of plastic (hard) found in the SRF stream was 70% of its input mass to MT plant. Plastics are the main components contributing to high calorific values in the fuel (Susanne et al., 2004). The mass fraction of plastic (hard) found in the reject stream was 20% of its input mass to MT plant. Use of NIR sorting technology in newly built MBT plants is capable of reducing the total chlorine content of SRF by removing highly chlorinated plastic components (Schirmer et al., 2007). Most of the components of plastic (hard) found in the reject stream were found to be PVC-plastics. Major mass fraction of rubber component was found in the reject stream which was 56% of its input mass.

6. Conclusion

The fraction of commercial and industrial waste (C&IW) complicated to sort out for material recycling was used to produce SRF through mechanical treatment (MT). This process recovered a high yield of useful material in the form of SRF to be utilized for energy recovery and it also recovered recyclables such as metals (ferrous and non-ferrous). Material recovered in the form of SRF was 62% and in the form of recyclables (i.e. ferrous/non-ferrous metals) was 5% of the total input waste material (i.e. C&IW) to MT plant to produce SRF.

The energy recovered in the form of SRF was 75% of the total input energy content of C&IW to MT plant. Energy consumed in processing the C&IW to produce SRF through MT was calculated in terms of inplant and outplant operations. For this specific process energy consumed on outplant operations was about 2.2 times of energy consumed on inplant operations.

In the composition of C&IW paper and cardboard and plastics (soft and hard) were the major components i.e. 31% and 31.6% by mass respectively of its composition (wet basis). The stream of SRF produced from C&IW was enriched with paper and cardboard and plastics. Mass fraction of paper and cardboard and plastics (soft and hard) in the SRF was 35.6% and 40.5% respectively of tis composition. The reject stream produced in this process mainly contained inert material components (such as glass, stone/rock, fines), plastic (PVC-plastic) and rubber material. A noticeable mass fraction of combustibles (paper and cardboard and wood) was also found in the reject stream. Most of the components (paper and cardboard and wood) in the reject stream were found to be highly moist, large in particle size (>200 mm) or irregular in shape.

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PAPER II

Elemental balance of SRF production process: Solid recovered fuel produced from commercial and industrial waste

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Elemental balance of SRF production process: Solid recovered fuel produced from commercial and industrial waste

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HIGHLIGHTS

- Concentration of inorganic elements in waste components is examined.
- Concentration of inorganic elements in streams of SRF production process is examined.
- Sources of pollutant and potentially toxic elements in input waste are identified.
- Elemental balance of commercial scale SRF production process is established.
- Parameters affected the quality of SRF and yield of SRF process are highlighted.

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ABSTRACT

In order to study the mass flow of pollutant and potentially toxic elements (PTEs) in the output streams of solid recovered fuel (SRF) production process, the various streams produced in commercial scale SRF production process are characterized chemically and, the elemental balance of SRF production process is presented. The SRF is produced from commercial and industrial waste (C&IW) through mechanical treatment (MT). The elements investigated for their mass balance in SRF production process are chlorine (Cl), arsenic (As), cadmium (Cd), lead (Pb) and mercury (Hg). The results showed that of the total input chlorine 60% was found in the SRF stream and 35% in the reject material stream and rest of 5% was in fine fraction and heavy fraction streams. Of the total input arsenic content 42% was found in the reject material and 32% in the SRF stream and rest (i.e. 26%) was found in the fine fraction stream. In case of cadmium, lead and mercury of their total input content to the process 46%, 58% and 45% respectively was found in the SRF stream. Among the waste components of C&IW, rubber and plastic (hard) were measured to contain the highest content of chlorine i.e. 8.0 wt.% (dry basis) and 3.0 wt.% (dry basis) respectively. Rubber was also found to contain higher content of cadmium as compared to other waste components. Plastic (hard) was measured to contain higher content of lead (i.e. 400 mg/kg, dry basis) than other components of input waste stream. The distribution of waste components (mainly plastic (hard), rubber and to some extent textile) was found significantly more important than other components of input waste stream in defining the concentration of pollutant and potentially toxic elements in output streams of SRF production process.

1. Introduction

Production and use of solid recovered fuel (SRF) represent a sustainable alternative for waste material that cannot be used for recycling due to economic inefficiency [1,2]. To recover value from the non-sustainably recyclable waste fraction, SRF can be a practical and environmentally safe outlet [3]. Use of SRF is significantly beneficial in terms of its utilization as an alternative energy source and a potential incorporation of the biogenic content of initial waste stream which is carbon dioxide (CO_2) – neutral [4,5]. To save primary fuels energy intensive industries are looking for alternative fuels, which encourage the sustainable development [6–10].

Use of SRF as fuel in coal fired power plants, cement and lime producing industries requires high quality standards in order to replace fossil fuels and so as not to cause operative and technical problems. The reliable quality standards in terms of fuel characteristics (chemical and physical) are one of the quality criteria that have to be ful-

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filled by SRF [1]. Thus, SRF is subject to stringent quality standards. In 2003, CEN (European Committee for Standardization) TC 343 was established to develop standards and technical specifications for solid recovered fuels for European markets. European standards for SRF have been established, the standardisation process took some ten years in which a lot of information on SRF has been generated [11–13]. The classes and specifications of SRF have been described and evaluated based on various parameters (such as net calorific value, chlorine content and mercury content) in CEN standards for SRF [6,14]. Technical prospects for the production and use of SRF have improved due to decades of profound experiences in cement and power plant industries. The production and use of SRF is an area where 'science meets practice' [15].

By the early 1990s, an initial disaster cycle for refuse-derived fuels (RDF) was effectively closed and the term ended up denoting a low-quality fuel or absence of quality checks [3]. RDFs could not create sufficient demand because of the high concentrations of chlorine and heavy metals in it. The non-homogeneous distribution of elements like chlorine, cadmium and mercury in waste components leads to varying fuel qualities [16,17]. As chloride salts they have significant influence on corrosiveness of deposits on the superheater tubes. From an emission perspective, SRFs can be considered "clean" fuels, if their content of heavy metals is below certain levels. Therefore, as a general rule heavy metals concentrations need to be kept as low as possible [18]. Zinc, lead and tin lower the melting temperature of deposits on the superheater tubes amplifying corrosion [19]. Trace elements that can be volatized in the combustion processes, with insufficient additional flue gas cleaning they can be released as gaseous emissions. Trace and major elements affect the composition of ash [20].

Commercial and industrial waste (C&IW) [21] possesses a significant potential in terms of energy fuel to be utilized for energy recovery [22]. C&IW contains a very high mass fraction of combustibles (such as paper and cardboard, plastic and textile) along with considerable mass fraction of impurities (such as PVC plastic, highly chlorinated rubber material and inert material). In the previous research [21] most of the combustibles in C&IW were recovered in the form of SRF by sorting out the impurities in separate small streams.

Input waste material and production technology affect significantly the quality of SRF [23,24]. The phenomenon of peak concentration in fuel product is reduced by mechanical processing of waste material. However, variability in fuel properties is unavoidable [25]. Based on the unit operations/sorting techniques used in an SRF production plant, various streams of material are produced in the process. Highly pollutant and low quality waste components are concentrated separately in small streams to produce relatively less polluted and quality controlled stream of fuel product [16,21,26]. Proper sorting of input waste stream's components into output streams ensures high quality of SRF stream. Chemical characteristics of output streams of refuse derived fuel (RDF) production processes are evaluated in a previous research [16]. There are only very few published studies [16,27–29] which cared about chemical characteristics and elemental material flow in output streams of SRF/RDF production processes.

The objective of this paper is to study the mass flow of pollutant and potentially toxic elements into various output streams of SRF production process produced from commercial and industrial waste (C&IW). This research examined in detail, the concentration of inorganic elements in various streams and components produced in commercial scale SRF production process produced from C&IW. Based on the elemental analysis of process streams, the elemental balance of SRF production process is established by using material flow analysis (MFA) approach. In this paper also, source components of pollutant and potentially toxic elements are identified based on the elemental analysis of components of input waste stream (i.e. C&IW).

2. Materials and methods

A commercial scale experimental campaign was conducted to produce SRF from C&IW. A batch of 79 tonnes of C&IW was collected from the metropolitan area of Helsinki region was treated on MT waste sorting plant to produce SRF. Based on the unit operations and sorting techniques used in MT plant, input waste material was further divided into various output streams of material; SRF, ferrous metal, non-ferrous metal, fine fraction, heavy fraction and reject material. All the process streams were sampled and treated according to CEN standard methods for SRF: EN15442 [30]. As per EN 15442, sampling of streams from SRF production plant was performed by using static lot method and manual drop flow method. Sample preparation of process streams for their laboratory analysis was performed as per CEN standard methods for SRF: EN 15443 [31]. As per EN 15443, methods of particle size reduction and sample division (mass reduction) were applied at every stage of sample preparation of streams for laboratory analysis. Standard analysis methods used for the elemental analysis of waste components and process streams in laboratory were; SFS-EN ISO 10304-1:2009 (mod.) for halogens, SFS-EN ISO 11885:2009 (mod.) for major elements/heavy metals and SFS-EN ISO 17294-2:2005 (mod.) for minor/trace elements. Laboratory analysis of major elements, minor elements and halogen was based on elementary analysis inductively coupled plasma optical emission spectrometry (ICP-OES), inductively coupled plasma mass spectrometry (ICP-MS) and liquid chromatography of anions and ion chromatography methods respectively. Details about description of SRF production process (unit operations/sorting techniques), sampling of process streams from SRF production plant and their sample preparation for laboratory analysis are published in a previous study [21].

Here, the elemental balance of SRF production process are based on the elemental analysis of various streams produced in this process and are calculated by using material flow analysis (MFA) method. MFA is a systemic assessment of material flows within a system defined in space and time. In waste treatment processes, whereabouts of hazardous chemicals can be determined only by an exact accounting of all substance flows [16]. The methodology on MFA is published [32,33].

The configuration of SRF production plant (in terms of unit operations used) and their arrangement in the process have profound implications on the outcome of the process. Unit operations/sorting techniques used in the SRF production process were primary shredding, screening (jigging and drum screens), metal separation (magnetic/eddy current separators), air classifiers, near-infra red (NIR) sorting units and secondary shredding. Input waste stream (i.e. C&IW) passed through series of these unit operations in which components were sorted out into various output streams based on material properties e.g. particle size (screening), density/weight (air classifier), magnetic properties (magnetic separation) and IR-spectra (NIR sorting). Detailed description of unit operations used in SRF production process and their functions is presented in a previous study [21].

Concentration of thirty elements in various process streams (input and output) was measured in laboratory (see Table 2). The elements investigated for their balance in SRF production process were; chlorine (Cl), arsenic (As), cadmium (Cd), lead (Pb) and mercury (Hg). These are potentially toxic elements which could be found in fuel product. It is reported [16] that in the RDF production test runs chlorine, lead and cadmium have been often found concentrated in fuel product. The SRF production process evaluated in order to establish elemental balance by using MFA is shown in Fig. 1. In the given MT process, incoming waste material stream i.e. C&IW is subjected to mechanical separation to produce SRF. This process only does the mechanical separation of the incoming

Table 1
Laboratory elemental analysis of components of input waste stream of commercial and industrial waste (mean value of three laboratory sub-samples test).

#	Element	Unit	Paper and cardboard	Plastic (hard)	Plastic (soft)	Textile	Rubber	Foam	Wood	Fines
1	Cl	wt%, d	0.2	3.0	0.14	1.0	8.0	0.2	0.075	0.4
2	Br	wt%, d	<0.001	0.002	<0.001	0.06	<0.001	0.002	<0.001	0.002
3	F	wt%, d	0.002	0.002	0.002	0.003	0.002	0.002	<0.001	0.007
4	S	wt%, d	0.1	0.08	0.08	0.2	0.5	0.1	<0.02	1.0
5	Na	mg/kg, d	2300	820	2800	2300	1100	1000	780	26,400
6	K	mg/kg, d	1100	570	2000	1700	1200	1100	990	9700
7	Ca	mg/kg, d	39,500	16,200	14,800	21,100	75,400	14,200	2500	66,800
8	Mg	mg/kg, d	1700	2200	1400	860	11,300	860	280	6,000
9	P	mg/kg, d	230	240	550	330	420	290	120	1,500
10	Al	mg/kg, d	11,400	3300	4600	2600	2900	1500	510	23,200
11	Si	mg/kg, d	9000	6100	16,300	9400	17,500	5300	1700	57,100
12	Fe	mg/kg, d	1100	1000	8000	1700	1900	1500	690	19,400
13	Ti	mg/kg, d	920	3500	4000	1000	4400	740	330	10,200
14	Cr	mg/kg, d	12.0	77.0	33.0	360	1300	20.0	7.3	270
15	Cu	mg/kg, d	20.0	3.6	78.0	21.0	1400	16.0	5.0	500
16	Mn	mg/kg, d	48.0	57.0	76.0	120	47.0	32.0	75.0	260
17	Ni	mg/kg, d	6.0	27.0	14.0	12.0	21.0	7.7	5.7	150
18	Zn	mg/kg, d	87.0	370	420	150	5500	260	83.0	1400
19	Sb	mg/kg, d	4.4	84.0	12.0	360	27.0	41.0	1.2	23.0
20	As	mg/kg, d	<0.5	0.6	1.0	2.0	1.2	1.6	<0.5	5.5
21	Ba	mg/kg, d	55.0	240	280	120	1300	420	31.0	1300
22	Cd	mg/kg, d	0.1	2.7	0.2	0.2	11.0	0.1	0.16	1.3
23	Co	mg/kg, d	2.0	3.3	180	31.0	2.0	2.0	0.8	12.0
24	Pb	mg/kg, d	9.5	400	76.0	17.0	250	16.0	3.0	320
25	Mo	mg/kg, d	0.7	3.7	3.0	3.5	2.2	4.2	<0.5	1,300
26	Se	mg/kg, d	<0.5	0.5	<0.5	0.5	0.6	0.5	<0.5	3.0
27	Tl	mg/kg, d	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
28	Sn	mg/kg, d	2.0	13.0	9.8	5.3	100	260	0.6	36.0
29	V	mg/kg, d	3.7	1.8	4.2	2.7	17.0	2.6	0.7	18.0
30	Hg	mg/kg, d	<0.05	0.05	0.1	0.2	0.08	0.2	<0.05	0.3

Table 2
Elemental analysis of various streams produced in SRF production process: SRF produced from commercial and industrial waste (mean value of three laboratory sub-samples test).

#	Element	Unit	Input waste stream (C&IW)	Reject material stream	Fine fraction stream	SRF stream
1	Cl	wt%, d	0.6	1.2	0.4	0.6
2	F	wt%, d	0.007	0.008	0.01	0.01
3	Br	wt%, d	0.005	0.3	0.006	0.003
4	S	wt%, d	0.2	0.3	0.8	0.3
5	Na	mg/kg, d	2995	4453	23,300	3458
6	K	mg/kg, d	2153	2904	8800	2174
7	Ca	mg/kg, d	18,533	39,543	57,000	36,260
8	Mg	mg/kg, d	1591	2420	5200	1482
9	P	mg/kg, d	870	774	1,600	958
10	Al	mg/kg, d	7301	14,230	19,900	8200
11	Si	mg/kg, d	22,183	25,023	58,600	18,871
12	Fe	mg/kg, d	4399	4162	12,000	4841
13	Ti	mg/kg, d	3089	2130	5700	3162
14	Cr	mg/kg, d	290	79	190	48
15	Cu	mg/kg, d	5,803	1,016	330	375
16	Mn	mg/kg, d	112	97	210	79
17	Ni	mg/kg, d	22	44	94	22
18	Zn	mg/kg, d	4118	542	1000	336
19	Sb	mg/kg, d	7.2	1,158	31	52
20	As	mg/kg, d	5.0	7.0	9.8	1.8
21	Ba	mg/kg, d	290	416	880	287
22	Cd	mg/kg, d	1.2	1.5	1.0	0.6
23	Co	mg/kg, d	2.4	4.8	11	3.6
24	Pb	mg/kg, d	90	150	235	120
25	Mo	mg/kg, d	3.0	4.3	10	3.6
26	Se	mg/kg, d	0.5	<0.5	1.7	0.5
27	Tl	mg/kg, d	<0.5	<0.5	<0.5	<0.5
28	Sn	mg/kg, d	8.8	34.1	23	18.8
29	V	mg/kg, d	6.0	7.7	16	5.3
30	Hg	mg/kg, d	0.1	0.2	0.4	0.1

material and no material transformation takes and moreover, it does not store any material in it. Based on the law of mass conservation; the input mass balance of element (s) was calculated from sum of its mass in output streams. Metals of each stream were not included in the elemental balance.

The elemental balance of input waste stream was calculated from the sum of mass of element in the output streams by using Eq. (1).

$$X_{\text{input}}(s) = M_{\text{input}} \cdot C_{\text{input}}(s) = \sum_{i=1}^{k} M_{P_i} \cdot C_{P_i}\ (s) \tag{1}$$

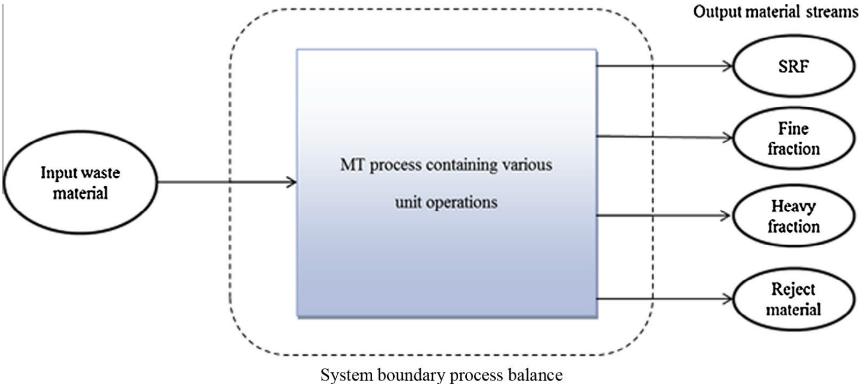


Fig. 1. Flow balance of MT process to produce SRF.

where X is the load of element; c is the concentration of element; M refers to the mass of stream; P_i refers to the output $_i$; (s) refers to the element; and k number of outputs.

In combination with the composition of input waste stream and elemental analysis of waste components, specific load contribution of various elements in unsorted waste stream (i.e. input waste stream of C&IW) was determined. In order to calculate the specific load of an element in input waste stream, the mass fraction of that component in input waste stream was multiplied with the concentration of the element in that component of input waste stream. Composition of input waste stream is published in a previous study [21] and concentration of elements is taken from elemental analysis of components (see Table 1). The specific load contribution of an element in the components of input waste stream was based on the weight% of component (on dry basis) in the waste stream and concentration of element in that component on dry basis as well.

Determination of uncertainty aspects in sampling (sampling of streams from SRF production plant) and sub-sampling (sample preparation of process streams for laboratory analysis) was not addressed for this work, as it required very extensive sampling quantities and was almost not feasible for the sampling and sub-sampling of all the process streams (input and output) at this scale of research. The determination of the precision of the sampling and sub-sampling methods for SRF is presented in details in QUOVADIS document [34]. In this research work, the confidence in measured and calculated values (for elemental analysis of waste components, specific load contribution calculations and elemental balances in SRF production process) is based on the fact that the sampling of process streams from SRF production plant and sample preparation for laboratory analysis were conducted by using CEN standard methods [30,31]. The values of elements for elemental analysis of components of input waste stream and process streams (in Tables 1 and 2) are mean values of three laboratory test samples.

3. Results and discussions

The results include a detailed elemental analysis of components of input waste stream and process streams (input and output) produced in a commercial scale SRF production process. Here, by elemental means halogens, major elements/heavy metals and minor/trace elements. Components of input waste stream included paper and cardboard, plastic (soft), plastic (hard), textile, rubber, foam, wood and fines. Process streams included input stream (i.e. C&IW) and output streams; SRF, fine fraction, heavy fraction and reject material.

3.1. Elemental analysis of components of input waste stream (C&IW)

A detailed elemental analysis of components of input waste stream was performed in laboratory.

Source of pollutant and potentially toxic elements of input waste stream were identified based on the elemental analysis of waste components. Composition of input waste stream [21] and elemental analysis of waste (input waste) components (See Table 1) facilitated to determine the specific load contribution of elements in unsorted waste material (i.e. input stream of C&IW). Concentration of various elements in waste components and their specific load contribution in unsorted C&IW (input waste stream) is shown in Fig. 2.

Rubber and plastic (hard) were found to be the major sources of chlorine in unsorted input waste stream. The content of chlorine measured in these two components was 8.0 wt% (dry) and 3.0 wt% (dry) respectively. Rubber material also contained components of shoes in it. Plastic film, packaging plastic and shoe have been reported [27] to bear highest total chlorine concentration among the SRF components. More studies [16,28,29] report a very high concentration of chlorine in waste components of plastic, rubber, leather and shoes. It is reported in a research [35] that major portion of organic chlorine was found in rubber and plastic. Textile was found to contain higher content of bromine (Br) and antimony (Sb) as compared to other waste components. The content of bromine and antimony in textile measured in laboratory were 0.06 wt.% (dry) and 360 mg/kg (dry) respectively. This was a textile (synthetic). Flame retardant textiles have been reported [36–38] as one of the main source material of bromine. Rubber material was also found to be a major source of copper (Cu). Rubber contained 1400 mg/kg (dry) of copper in it. After rubber, fines were measured to contain 500 mg/kg of copper content. Rubber and fines were found to be major source components of zinc (Zn) as well. In rubber and fines the content of zinc measured was 5500 mg/kg (dry) and 1400 mg/kg (dry) respectively. High zinc content in rubber as municipal solid waste (MSW) component and rubber as a source of zinc is reported in literature [39,40]. Other source components of zinc in input waste stream were plastic (soft), plastic (hard) and foam material containing 420 mg/kg, d 370 mg/kg, d and 260 mg/kg, d of zinc respectively. In waste material, components of rubber, plastic products and fines are reported [16] contain high concentration of zinc.

Components of plastic (hard) and rubber were measured to contain 400 mg/kg, d and 250 mg/kg, d of lead (Pb) content respectively. In fines, lead content was measured as 320 mg/kg, d. The concentration of lead is reported in plastic products and fines as

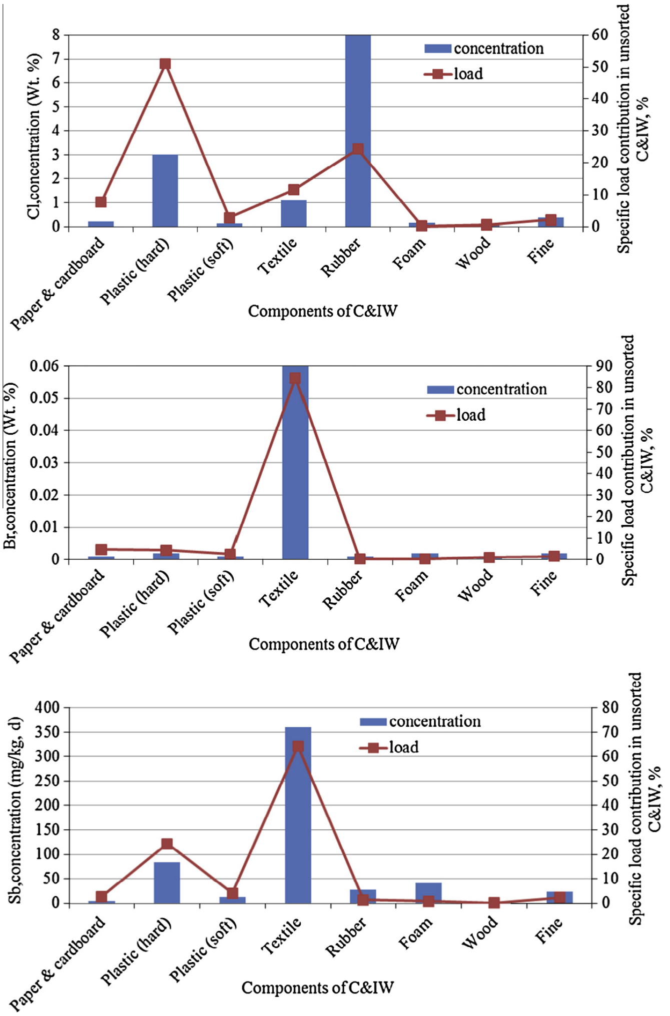


Fig. 2. Concentration of various elements in waste components and their specific load contribution in unsorted C&IW (input waste stream).

500 ppm and 200 ppm respectively in another research [16]. Mercury content of 0.3 mg/kg, d was measured in fines. The concentration of cadmium measured in rubber material was higher than in other components of input waste stream i.e.11 mg/kg, d. In another study [16] rubber is reported to contain about same concentration of cadmium.

In the elemental analysis of input waste stream's components, rubber was found to be the most problematic material in terms containing very high concentration of pollutant and potentially toxic elements. After rubber other problematic components identified were plastic (hard) and textile. The elemental analysis of various components of input waste stream (i.e. C&IW) to produce SRF is given in Table 1.

High load of chlorine, cadmium and lead in input waste stream of C&IW was found to be belonged to plastic (hard) components. Of the total load of chlorine, cadmium and lead in input waste stream 51%, 47% and 59% respectively was calculated to be contained by plastic (hard) component. The load of bromine and antimony in input waste stream was found to be dominated by textile (especially due to flame retardant textile components). Of the total load of bromine and antimony in input waste stream 84.6% and 64.3% respectively was calculated to be contained by textile component. Major load of copper was found to be contained by rubber material i.e. 43.4% of its total load in input waste stream. Half (51%) of the total load of mercury in input waste stream was calculated to be belonged to plastic (soft) component. Major load of arsenic calculated belonged with fines i.e. 29% of its total load in input waste stream. The load of arsenic calculated was found to be distributed comparatively homogenously among paper and cardboard, plastic (soft) and textile i.e. 18%, 18% and 19% respectively of their total load in input waste stream. Components of input waste stream (i.e. C&IW) analyzed in laboratory for their elemental analysis are shown in Fig. 3.

3.2. Elemental balance of SRF production process produced from C&IW

The elemental balances of SRF production process in input and output streams were calculated by using material flow analysis (MFA) methodology (see Section 2). Based on the results obtained from elemental balance of SRF production process, of the input

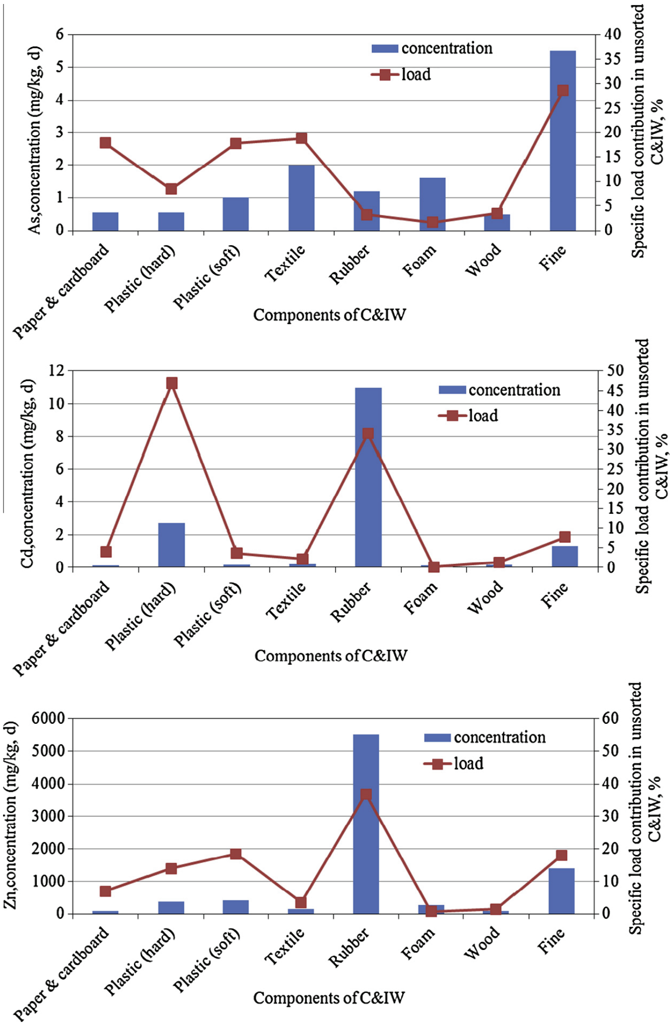


Fig. 2 (*continued*)

chlorine (Cl) and lead (Pb) content, higher mass was found in the SRF stream as compared with other output streams (see Fig. 4). Cadmium (Cd) was found to be relatively homogenously distributed between SRF and reject streams of its input content i.e. 46% and 40% respectively and rest was in fine and heavy fraction streams. Of the input concentration (mass) of arsenic 42% and 26% was found in the reject and fine fraction streams respectively and 32% in the SRF stream. Of the input concentration (mass) of mercury (Hg), 45%, 30% and 25% was found in the SRF, reject and fine fraction streams respectively. The concentration of these elements in the output streams was found to be significantly affected by the distribution of plastic (hard), rubber and textile components of input waste stream. The elemental balance of SRF production process: SRF produced from C&IW through MT is shown in Fig. 4 in the form of sankey diagrams. Heavy fraction stream was not analyzed in the laboratory for its elemental analysis, mass fraction was relatively very small (i.e. 0.3%) as compared with the other streams and in its composition the major components were inert [21]. Elemental balance of heavy fraction stream was based on its composition and elemental analysis the components. The difference in the measured and calculated values of element concentration in input waste stream was calculated as balance error (%). Different colors in sankey diagrams indicate the intensity of polluted stream for example, red color indicate the highest polluted stream after that yellow and blue colors respectively and green color indicates the least polluted stream.

A considerable mass fraction of combustibles (especially paper and cardboard and wood) of their input mass was found in the reject stream. The components of paper and cardboard and wood found in the reject stream were either large in particle size (>250 mm), irregular in shape (e.g. paper in rolled form) or highly moist (heavy in weight) [21,23,26]. These components of paper and cardboard and wood were not supposed to be in the reject stream but in the SRF stream. Based on the observations, heavy weight (due to high moisture content) and irregular shape (due to large particle size and bundle form) of components (paper and cardboard and wood) and high/sudden mass flow (due to sometimes non-steady/sudden feeding of input waste material by exca-

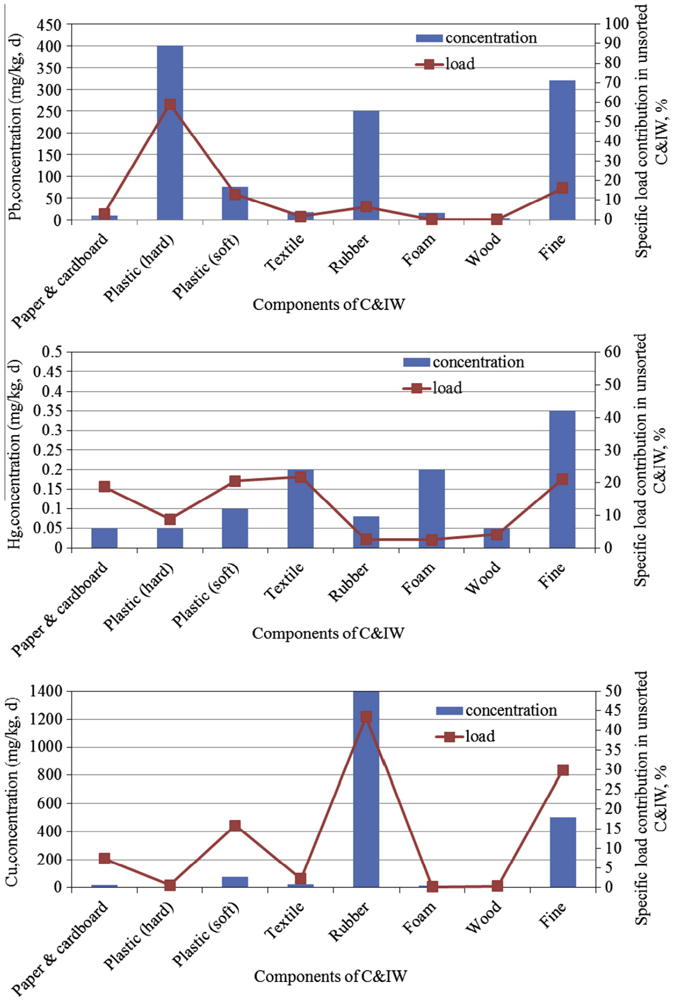


Fig. 2 (*continued*)

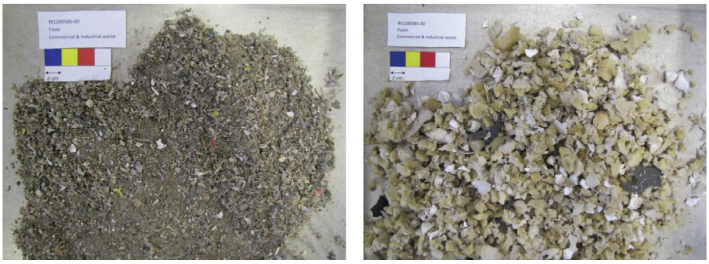
vator i.e. material loader at the start of process) affected the function of unit operation (air classifier and NIR sorting units) and therefore, these combustible were not got sorted out properly into the SRF stream but rather ended up in reject stream. The chlorine content of paper and cardboard and wood were measured as 0.2 wt.% (dry) and 0.075 wt.% (dry) (see Table 1) respectively which means that presence of these component in the SRF stream would have effectively reduced the chlorine content of SRF. Paper/card is reported to lower the chlorine content in the fuel i.e. RDF/SRF [16,27]. In the composition of SRF [21], mass fraction of plastic (hard) and textile was 16.5 wt.% and 8.5 wt.% respectively. The chlorine content measured in plastic (hard) and textile was 3.0 wt.% (dry) and 1.0 wt.% (dry) respectively. The high mass flow of chlorine into the SRF stream could be due to the high mass fraction of plastic (hard) and to some extent textile (synthetic type) components. There might be some light weight components (plastic, textile or some other) carrying pollutant or potentially toxic elements (chlorine, lead and cadmium) could have been taken away by air classifier and put into the SRF stream. Plastics are reported [29] to carry chlorine load in fuel product (SRF).The second higher mass flow of input chlorine was found in the reject stream i.e. 35%. This was due to the mass fraction of rubber and PVC-plastic in the reject stream [21]. Chlorine content of rubber was measured as 8.0 wt.% (dry). This rubber material also contained rubber shoes in it.

Mass flow of arsenic (As) was found higher in reject stream as compared with the other streams of process. The content of arsenic measured in fines i.e. 5.5 mg/kg (dry) was higher than measured in other components of input waste stream. Other than fines the content of arsenic measured in textile, foam and rubber was 2.0 mg/kg (dry), 1.6 mg/kg (dry) and 1.2 mg/kg (dry) respectively. In the composition of reject stream [21] the mass fraction of fines, textile and rubber was 17 wt.%, 9.2 wt.% and 6.8 wt.% respectively. The mass flow of cadmium (Cd) calculated in the SRF and reject stream was 46% and 40% respectively of its input concentration to the process. The content of cadmium measured in rubber was higher than that of measured in other waste components. Major mass fraction of rubber was found in the reject stream of its input mass to the process. Of the total calculated input concentration of lead (Pb) 58% was found to get concentrated in the SRF stream and 24% in

Paper and cardboard Plastic (hard)

Plastic (soft) Wood

Textile Rubber



Fines Foam

Fig. 3. Components of input waste stream (i.e.C&IW) analyzed in laboratory.

reject material and 17% in fine fraction streams. High concentration of lead was measured in plastic (hard) component fines and rubber material. This high mass flow of lead in the SRF stream could be due to the high mass fraction of plastics in the composition of SRF stream. The mass flow of mercury (Hg) of its calculated input concentration was distributed among the streams of SRF, reject material and fine fraction as 45%, 30% and 25% respectively. High content of mercury was measured in plastic (soft) i.e. 0.4 mg/kg (dry). Other waste components after plastic (soft) were textile and fines containing 0.2 mg/kg (dry) and 0.3 mg/kg (dry) of mercury respectively. The mass fraction of plastic (soft) and textile in the SRF stream was 24 wt% and 8.5 wt% respectively of its composition [21].

In this SRF production process, wind shifters and near infra-red (NIR) sorting units play a key role in the distribution of combustible (paper and cardboard, non-PVC plastic, wood) and non-combustible (PVC-plastic and other highly chlorinated components, inert etc.) in the output streams of SRF and reject material. In wind shifter, components of input waste stream are sorted out on the basis of weight (density basis), and in NIR sorting waste components are separated based on their infra-red/spectral properties. The sorting processes are designed based on material properties

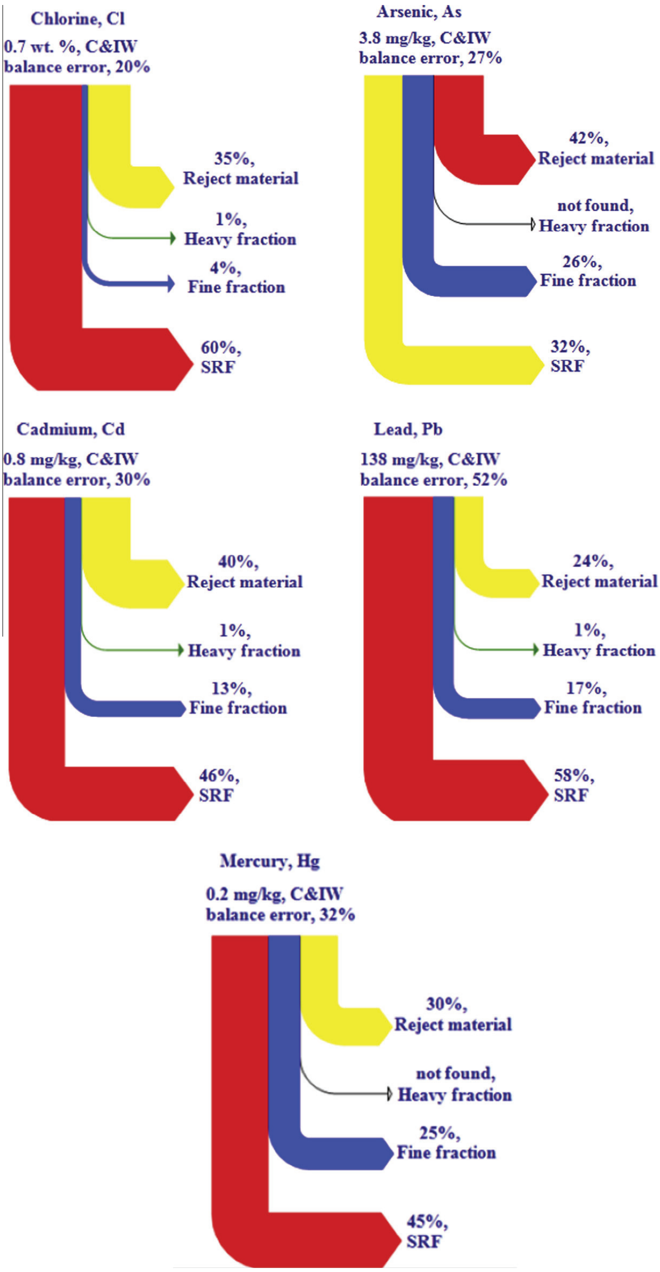


Fig. 4. Elemental balances of SRF production process: SRF produced from commercial and industrial waste (C&IW).

e.g. particle size (screening), density/weight (air classifier), magnetic properties (magnetic separation), IR-spectra (NIR sorting), and not on elemental basis in principle. NIR sensor-based sorting experiments showed that the technology is generally applicable to remove pollutants (mainly Cl and heavy metal bearing components), if the sensor systems are appropriately adjusted for the sorting task [41]. NIR units were not able to recognize black components because of black conveyor belt. It is reported [41] that dark plastics contained in the waste could significantly decrease the efficiency of the NIR sensor-based sorting technology (dark particles show a very low reflection of NIR light and can therefore not be identified correctly). The detailed laboratory elemental analysis of various streams produced in SRF production plant: SRF produced from C&IW through MT is given in Table 2.

The light weight components which contain higher concentration of pollutant elements (especially chlorine and cadmium) could be taken away by air classifier and put into SRF stream. This issue might be addressed by passing the air classified components through NIR sorting unit before putting them into SRF stream. The light weight components (air classified) having higher concentration of pollutant element (especially chlorine) could be sorted out by NIR sorting unit (through negative sorting) into reject material stream instead of entering into SRF stream. Better particle size distribution in primary shredding in terms of particle size and shape and by adding drying operation in the process could have improved the sorting efficiency of air classifiers (especially components of wood, paper and cardboard and textile found in the reject material were bigger in size >250 mm, paper in the form of bundles and highly moist) to enhance the yield and quality of SRF. The addition of 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 relevant option is bio drying in terms of the bioprocess operation for mechanical biological treatment (MBT) plants, and there is a peer-revived review publication covering how bio drying is used for MBT treatment of wastes [42]. Traditional drying using fossil fuel is not used that much anymore due to cost. It is worth mentioning here that to balance mass flows of the plant by (first of all) careful feeding of input waste by excavator (i.e. mechanical front loader) (not to try to feed as much as possible) and 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, maintenance is also important (e.g. keeping clean air nozzles of NIR units), ensure that machines are working properly and setups are correct.

4. Conclusion

This research examined in detail, the concentration of inorganic elements in various streams of material produced in commercial scale solid recovered fuel (SRF) production process and components of input waste. The SRF was produced from commercial and industrial waste (C&IW). The elemental balance of SRF production process was calculated by using material flow analysis (MFA) methodology. The potential source material of pollutant and potentially toxic elements in the components of C&IW stream are traced and identified.

Of the total input chlorine, arsenic, cadmium, lead and mercury content to the process 60%, 32%, 46%, 58% and 45% respectively was found in the SRF stream. Among the components of C&IW, rubber and plastic (hard) were measured to contain the highest content of chlorine (i.e. 8.0 wt% and 3.0 wt% respectively) and identified as potential source of chlorine. Rubber also contained high content of cadmium as compared to the other components. Plastic (hard) was measured to contain higher content of lead as compared with other components of input waste stream.

The distribution/sorting of rubber, plastic (hard) and to some extent textile components played key role in defining the concentration of pollutant and potentially toxic elements in output streams of SRF production process. A considerable mass fraction of paper and cardboard and wood found in the reject stream could have effectively reduced the overall concentration of pollutant and potentially toxic elements of SRF, if those were sorted and put into the SRF stream instead of ending up in reject material stream. The elemental based sorting of waste components is required in order to further reduce the content of pollutant and potentially toxic elements in the SRF stream.

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PAPER III

Mass, energy and material balances of SRF production process. Part 2: SRF produced from construction and demolition waste

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Mass, energy and material balances of SRF production process. Part 2: SRF produced from construction and demolition waste

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ABSTRACT

In this work, the fraction of construction and demolition waste (C&D waste) complicated and economically not feasible to sort out for recycling purposes is used to produce solid recovered fuel (SRF) through mechanical treatment (MT). The paper presents the mass, energy and material balances of this SRF production process. All the process streams (input and output) produced in MT waste sorting plant to produce SRF from C&D waste are sampled and treated according to CEN standard methods for SRF. Proximate and ultimate analysis of these streams is performed and their composition is determined. Based on this analysis and composition of process streams their mass, energy and material balances are established for SRF production process. By mass balance means the overall mass flow of input waste material stream in the various output streams and material balances mean the mass flow of components of input waste material stream (such as paper and cardboard, wood, plastic (soft), plastic (hard), textile and rubber) in the various output streams of SRF production process. The results from mass balance of SRF production process showed that of the total input C&D waste material to MT waste sorting plant, 44% was recovered in the form of SRF, 5% as ferrous metal, 1% as non-ferrous metal, and 28% was sorted out as fine fraction, 18% as reject material and 4% as heavy fraction. The energy balance of this SRF production process showed that of the total input energy content of C&D waste material to MT waste sorting plant, 74% was recovered in the form of SRF, 16% belonged to the reject material and rest 10% belonged to the streams of fine fraction and heavy fraction. From the material balances of this process, mass fractions of plastic (soft), paper and cardboard, wood and plastic (hard) recovered in the SRF stream were 84%, 82%, 72% and 68% respectively of their input masses to MT plant. A high mass fraction of plastic (PVC) and rubber material was found in the reject material stream. Streams of heavy fraction and fine fraction mainly contained non-combustible material (such as stone/rock, sand particles and gypsum material).

1. Introduction

Waste material can be turned into a valuable asset by the recovery of useful material and energy from it. The recovery of material and energy are not an adversary practices but both of these are essential elements of a virtuous waste management system (European Commission, 2008). In order to save the primary fuels, energy intensive industries are looking for alternative fuels. In this regard the waste management sector has developed ways to produce secondary fuels such as solid recovered fuel (SRF) (EN 15508). In Europe, solid recovered fuel (SRF) is prepared from non-hazardous waste to be utilized for energy recovery in incineration/co-incineration plants and meeting the classification and specifications requirements laid down in CEN standards (EN 15359). SRF is a high potential co-combustion fuel used in power plants and cement kilns but technological risks and environmental emissions are typically lower at cement kilns (Garg et al., 2009). The renewable content in SRF and its use in high efficiency processes make a significant and growing contribution to the mitigation of CO_2-emissions (N.N., 2008; Gehrmann, 2012). The advantages and potential of SRF have been gradually appreciated, and in Europe the production of SRF from non-hazardous waste is a growing industry (Hilber et al., 2007; Frankenhaeuser et al., 2008). A high quality SRF with constant composition which can guarantee the reliable plant operations is what power plants are looking for. The cement and lime producing industries as well as the coal fired power plants are interested in the SRF with homogenous composition and having guaranteed quality and availability (Glorious, 2012). Delivery of high quality SRF is connected with the

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type of input waste material and SRF production techniques (Wilén et al., 2002). In Europe, SRF is produced from various waste streams such as household waste (HHW), commercial and industrial waste (C&IW), construction and demolition waste (C&D waste) and some other selected waste streams.

Construction and demolition waste (C&D Waste) represents around 31% of total waste produced in the European Union (Rodrigues et al., 2013). Due to the high level of construction activity, management of C&D waste is a major issue worldwide (Zaragoza, 2008). According to the EU waste strategy C&D waste is considered as "priority" waste stream (Banias et al., 2011). The environmental problem posed by C&D waste is not only caused by its increased volume, but also from its treatment. Some of the environmental impacts are: contamination of soil and water resources by uncontrolled landfills, deterioration of the landscapes, and importantly economic impact due to waste elimination without recycling and re-use of material (Carlos et al., 2013). C&D waste is getting a special attention worldwide for its proper management and treatment.

A number of studies have been published which deal with C&D waste management (Yuan, 2012; Yuan et al., 2012; Hsiao et al., 2002; Zhao et al., 2010). There are not many published studies specifically regarding the management of C&D waste by recovery of energy from it in terms of SRF/RDF and especially studies which deal with the material flows and their characteristics in the various streams produced in SRF/RDF production process produced from C&D waste. This paper describes the production of SRF from C&D waste and flow of material and their characteristics in various streams produced in this SRF production process. It is important for SRF manufacturing operators to understand the materials flow of waste components (paper, plastics, wood, etc.) through their facilities to optimize plant configurations and produce SRF with predictable properties for end users (Velis et al., 2013).

In Finland, C&D waste contains more combustible material (especially wood) as compared to central Europe. At the moment in Finland, the fraction of C&D waste which is complicated and economically not feasible to sort out properly for material recycling purposes is being managed through MT plants to produce SRF. In these MT waste sorting plants impurities (such as metals, material having low calorific value, highly chlorinated/pollutant material) are selectively separated in small streams to produce a high yield of SRF stream which fulfils the quality requirements recommended by the CEN standards for SRF.

The objective of this paper is to analyze the material flows and characteristics of material in the various streams produced in SRF production process. This SRF is produced from C&D waste through MT. All the process streams produced in this SRF production plant were sampled and treated according to the CEN standard methods for SRF (EN 15442, EN 15443). The SRF produced from these MT plants is being utilized as a fuel/co-fuel in the dedicated gasification and combustion plants for the production of heat and power. Metals (ferrous/non-ferrous) are recycled and other streams such as fine fraction, heavy fraction and reject material are partly used for recycling, energy recovery, and environmental construction (landfill construction) and disposed to landfill.

The balances are presented in the form of sankey diagrams. Sankey diagrams are suitable way to visualize the mass and energy flow balances in which the width of arrow is proportional to the quantity of flow.

2. Materials and methods

A commercial scale experimental campaign was conducted to produce SRF from C&D waste. A batch of 74 tons of C&D waste was collected from the Metropolitan area of Helsinki region and transported to an MT waste sorting plant for its further sorting and treatment to produce SRF. This C&D waste represents the common demolition waste in this region. But the composition of C&D waste may vary with the location in other cities.

Based on the unit operations and sorting techniques used in MT plant the input waste stream (i.e. C&D waste) was further divided into various output streams: SRF, ferrous metal, non-ferrous metal, reject material, fine fraction and heavy fraction as shown in Fig. 1.

Classification of input waste stream into various output streams was based on particle size distribution, weight/density, ferrous/non-ferrous material and near-infrared (NIR)/specific spectral properties of input waste material's components. The function of NIR sorting unit in this MT process was to classify the combustible components (such as paper and cardboard, wood and non-PVC plastic) from input waste material and to put them into SRF stream. Sorting of NIR unit was based on the specific spectral properties of components of waste material.

Nominal top sizes (D_{95}) of input and output streams were:

- C&D waste, after primary shredding (D_{95} 150 mm), SRF (D_{95} 75 mm), fine fraction (D_{95} 10 mm), heavy fraction (D_{95} 150 mm), reject (D_{95} 85 mm), reject (D_{95} 120 mm), ferrous metal (D_{95} 150 mm) and non-ferrous metal (D_{95} 150 mm).

There were two streams of reject material separated in this process based on their particle size distribution i.e. reject (D_{95} 85 mm) and reject (D_{95} 120 mm). In Fig. 1 these reject streams are shown as a single stream of reject material.

In order to take representative samples of input and output streams from SRF production plant their sampling was done according to the CEN standard methods for SRF (EN 15442).

Based on the operational conditions and practical situation, methods used for the sampling of streams;

- Static lot method.
- Static conveyor belt method.
- Manual drop flow method.

Sampling quantities of process streams (input and output) taken from SRF production plant, their nominal top size, increment size and combined samples are given in Table 1.

As per EN 15442, increment size of process streams was based on their respective top nominal size (D_{95}) and bulk densities, and 24 increments of each stream (except ferrous metal, non-ferrous metal and heavy fraction) were taken from SRF production plant. Streams of ferrous metal, non-ferrous metal and heavy fraction were comparatively homogeneous in terms of their components (see Section 4) and therefore it was not realized to take more than 4 increments of each of these streams. The respective increments of process streams were combined together to form their combined samples.

After sampling of process streams from SRF production plant, next step was to prepare their respective samples for laboratory analysis. In order to keep the representativeness of original samples of process streams their further sample preparation for laboratory analysis was done according to EN 15443. Each stage of sample preparation involved:

- Particle size reduction.
- Sample division (mass reduction).

Equipment used for particle size reduction of process streams' combined samples was;

- Shredder, screens of various mesh sizes, cutting mill, crushing mill and grinding mill.

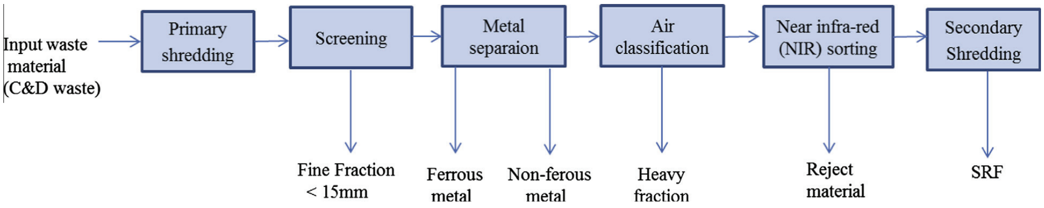

Fig. 1. Simplified flow chart diagram of MT based SRF production process.

Table 1
Sampling of process streams from SRF production plant.

Process stream	Nominal top size D_{95} (mm)	Increment size (kg)	Combined sample[a] (kg)
C&D waste (input stream)	150	20	480
SRF	75	2.5	60
Reject	85	5.0	120
Reject	120	10	240
Fine fraction	10	1.0	24
Heavy fraction	150	20	80
Ferrous metal	150	20	80
Non-ferrous metal	150	20	80

[a] Combined sample is sum of 24 increments for C&D waste, SRF, reject (D_{95} 85 mm), reject (D_{95} 120 mm) and fine fraction and sum of 4 increments for heavy fraction, ferrous metal and non-ferrous metal.

Methods applied for sample division (mass reduction) were;

- Manual increment division method.
- Riffle divider.

After sample preparation for laboratory analysis, final samples of process streams having particle size of 0.5 mm and 0.5–5 g in mass were analyzed in the laboratory. The reject streams i.e. reject (D_{95} 85 mm) and reject (D_{95} 120 mm) were combined together into one stream sample as a reject material for laboratory analysis. Samples of all the streams except metals (ferrous/non-ferrous) were analyzed in the laboratory. The details of process description, methods and procedures used for sampling of streams from SRF production plant and their sample preparation for laboratory analysis are described (Nasrullah et al., 2014).

3. Results and discussion

Samples of process streams: C&D waste (input waste), SRF, reject material, fine fraction and heavy fraction were analyzed in the laboratory. The analysis parameters for process streams were moisture content, ash content (550 °C), volatile matter, biomass content (Xbiomass, TC), heating value and CHONS measurements. Here, volatile matter refers to the part of SRF that on heating is released from it in gaseous form. Biomass content of SRF refers to the share (mass based) of biogenic carbon of the total carbon in it. The standard methods used for laboratory analysis of samples of process streams are listed in Table 2. Metals (ferrous/non-ferrous) in all process streams were not included in the laboratory analysis. Mass fraction of metals in each stream was known from the composition of process streams (see Section 4) and, therefore the laboratory analysis values were adjusted for each parameter of the streams and energy value of metals was taken as zero (Biffaward programme, 2003).

Heating value (NCV, dry) of this SRF stream produced from C&D waste was measured in laboratory as 20.0 MJ/kg. This heating value of SRF stream was due to the contribution of high mass fraction of wood, paper and cardboard and plastics in it. Heating value (LHV, MJ/kg) of SRF in the range of 18.6–23.56 has been reported in the literature (Vainikka et al., 2011). The biomass content of SRF was measured in laboratory as 66.7% C. This high biomass content was due to the strong contribution of wood and paper and cardboard in the SRF stream. Major part of biogenic waste fraction belongs to wood and paper and cardboard (Mohn et al., 2008; Fellner and Rechberger, 2009). It has been reported in the literature that SRF normally contains 40–80% of biogenic components (Hansen et al., 1998). For all the process streams except that of SRF a very high values of ash content were measured in laboratory. This was due to the high mass fraction of incombustible material such as building material (i.e. stone/rock, concrete and sand particles and gypsum material) in theses streams. As the input stream was C&D waste and, therefore the output process streams contained building material in high amounts. Major components in C&D waste are reported to be as building material (such as concrete, bricks, asphalt, gypsum, roofing and tiles and ceramics) (Franklin, 1998; Zhao et al., 2010; Spain ME, 2001).

Table 2
Standard methods used for the laboratory analysis of process streams.

Parameter	Standard methods
Moisture	E N 14774-2, CEN/TS 15414-2, ISO 589
Ash content 550 °C	EN 14775, EN 15403
Volatile matter	EN 15148, EN 15402, ISO 562
Biomass content	TYO 3.042 (EN 15440)
Heating value	EN 14918, EN 15400, ISO 1928
C, H, N, (O calculated)	EN 15104, EN 15407, ISO 29541
S	EN 15289, ASTM D 4239 (mod).

Laboratory analysis values of various parameters of process streams of SRF production plant produced from C&D waste are given in Table 3.

3.1. Mass and energy flows balances in process streams of SRF production process

Overall mass and energy flows balances of SRF production process were established to analyze the flow of mass and energy in the various output streams of SRF production process. Overall mass flow balance was made by weighing all the process streams (input

Table 3
Laboratory analysis of process streams produced in SRF production plant produced from C&D waste.

Process 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)	NCV (d.) (MJ/kg)
C&D waste	14.0	46.8	n.a.	n.a.	30.0	4.0	0.5	0.7	17	9.8	11.0
SRF	16.5	9.0	76.6	66.7	50.0	6.4	1.0	0.3	31.6	18.0	20.0
Reject material	12.0	47.2	n.a.	n.a.	31.2	3.8	0.6	0.7	16.2	10.0	12.0
Fine fraction	23.6	78.8	n.a.	n.a.	12.0	1.3	0.4	2.8	4.8	2.5	4.0
Heavy fraction	10.4	65.6	n.a.	n.a.	20.0	2.6	0.5	0.3	13.2	6.5	7.6

[a] Bio. cont. represents the biomass content (bio carbon) in % carbon.

and output) and overall energy flow balance was formed by calculating the energy balance of input waste stream from sum of the energy content of all the output streams of SRF production plant.

3.1.1. Mass flow balance in process streams of SRF production process produced from C&D waste

Overall mass flow balance of SRF production process was established for a batch of 74 tons of C&D waste material introduced to an MT waste sorting plant to produce SRF. All the output streams produced in this MT plant were weighed. This mass balance was based on the weight of input waste stream. The overall mass flow balance of SRF production plant produced from C&D waste is shown in Fig. 2.

Of the total input C&D waste material, 44% was recovered in the form of SRF. SRF is the process product utilized for the energy recovery in the dedicated CHP gasification and combustion plants. Metals (ferrous/non-ferrous) recovered from this process are recycled. A significant portion of input waste material (i.e. C&D waste) was sorted out in the form of fine fraction i.e. 28% by mass which was mainly consisted of shredded particles (<15 mm) of building material such as stone/rock, concrete, sand, glass and gypsum material. The streams of fine fraction, heavy fraction and reject material are partly used for environmental construction (landfill construction), energy recovery and disposed to landfill.

3.1.2. Energy flow balance in process streams of SRF production process produced from C&D waste

In this MT waste sorting process, the input waste material (i.e. C&D waste) was subjected to a mechanical separation and not to material transformation (in terms of physical/chemical changes, etc.) and, moreover the system does not store any material in it. Using the law of energy conservation, energy balance of input waste stream (i.e. C&D waste) was calculated from sum of the energy content of output streams. Total energy content of process streams were calculated by multiplying their net calorific value (MJ/kg) with their respective total masses. Net calorific values (MJ/kg) and moisture content of process streams were taken from the laboratory analysis of process streams (see Table 3) and their total masses were taken from mass flow balance in process streams of SRF production process (see Section 3.1.1.). Energy balance of SRF production process was made for both wet basis and dry basis of material of process streams. Energy values of the input waste stream (C&D waste) was measured in the laboratory (see Table 3) and it was calculated from the balance value as a sum of the output streams. The difference between the measured and calculated energy values of input waste stream was calculated as an error value. In case of energy balance made on wet basis the calculated value of the input energy was 18% higher than the measured value and in case of energy balance on dry basis the calculated value of the input energy was 16% higher than its measured value. Energy flow balances in process streams of this SRF production process produced from C&D waste on wet and dry basis are shown in Fig. 3.

Of the total input energy content of C&D waste to MT waste sorting plant 74% energy (wet basis of streams) and 72% energy (dry basis of streams) was recovered in the form of SRF and 16% (wet basis of streams) and 18% energy (dry basis of streams) was belonged with the reject streams respectively. Energy content of ferrous metal and non-ferrous metal streams was due to very small amount of combustibles (paper and cardboard, plastics, wood, etc.) in these streams and not due to the metals as energy value of metals was taken as zero. Composition of the process streams is given (see Section 4).

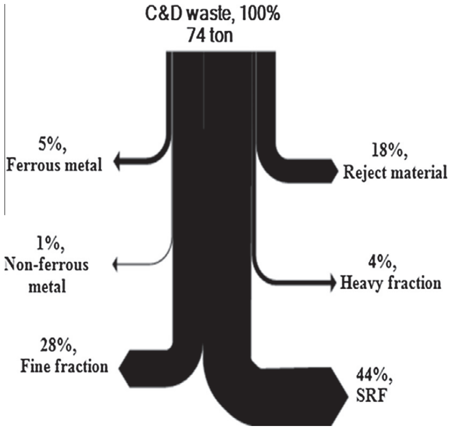

Fig. 2. Mass flow balance in process streams of SRF production process: SRF produced from C&D waste (wet basis).

3.2. Energy consumed in processing C&D waste to produce SRF

Energy consumed in processing the batch of 74 tons of C&D waste on MT waste sorting plant to produce SRF was divided into two operations:

- Inplant operations.
- Outplant operations.

Inplant operations comprised of the unit operations/sorting techniques used in MT plant such as shredding, screening, magnetic and eddy current separators, air classification, near-infrared (NIR) sorting unit, conveyor belts and dust extraction system and material handling machinery (wheel loaders and excavators). Outplant operations included the logistical operations (transportation of vehicles) in order to collect the batch of 74 ton of C&D waste from its collection points and to transport it to MT plant and it also included the transportation of the output process streams (i.e. SRF, metals, fine fraction, heavy fraction and reject material) to customer's premises. Energy consumed on inplant and outplant

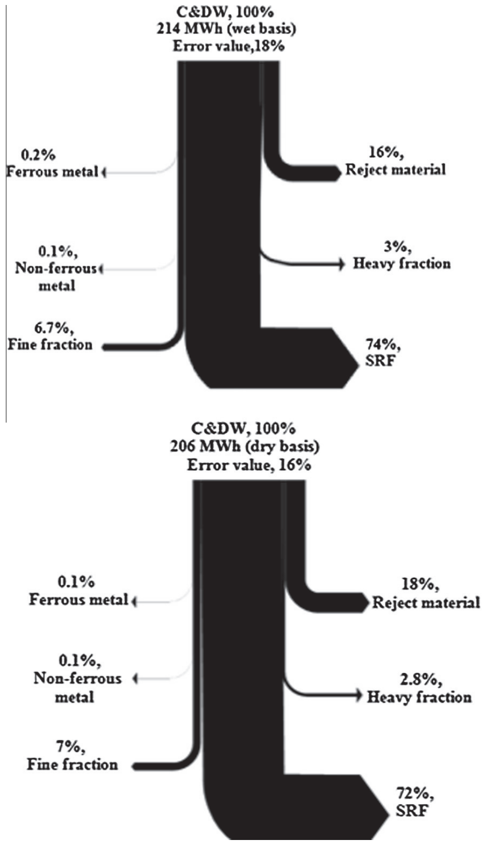

Fig. 3. Energy flow balances in process streams of SRF production process: SRF produced from C&D waste.

Table 4
Consumption of energy to process C&D waste on MT waste sorting plant to produce SRF.

Process	Unit	Energy consumption/*t* of input waste material
Inplant operations	kW h	50
Outplant operations	kW h	100

operations to process C&D waste on MT waste sorting plant to produce SRF is given in Table 4.

Consumption of energy for inplant operations was calculated/measured in kW h and for outplant operations (logistical operations) was calculated in terms of diesel consumption for trucks, lories, etc. and converted to kW h values. For this specific process of producing SRF from C&D waste, the energy consumed on outplant operations was two times the energy consumed on inplant operations.

4. Composition of process streams

By composition of process streams means their breakdown by types of contained material such as paper and cardboard, wood, plastic, textile, metal, rubber, stone/rock and glass and foam. The composition of process streams was determined by manual sorting of their respective combined samples (see Table 1) into their components. Composition of the process streams was based on wet mass basis of material.

This composition of C&D waste represents the common demolition waste of the Helsinki region area, but it may change with locations in other cities. Major component of C&D waste (input waste stream) was building material in the form of stone/rock, concrete and sand particles and gypsum material. Building material (in the form of stone, concrete, sand particles and gypsum) together with the fines formed 30.8% by mass of C&D waste's composition. Fines also mainly consisted of building material components (especially sand particles and some other shredded particles of stone, gypsum). Second major component in C&D waste after building material was wood i.e. 23.6% by mass. In Finland C&D waste contains more combustible material (especially wood) compared to central Europe. Other components found in considerable amount in C&D waste were paper and cardboard, metals and plastics (soft and hard) i.e. 12%, 10% and 9.6% by mass respectively. The stream of SRF produced from C&D waste was enriched especially with components of wood and paper and cardboard and plastics. In the composition of SRF the mass fraction of wood, paper and cardboard and plastics were 38%, 22% and 16% respectively. Composition of reject stream was found to be quite heterogeneous in terms of its components. Major component in reject stream was incombustible material (such as stone/rock, gypsum and glass particles). A noticeable mass fraction of combustibles (i.e. wood and paper and cardboard) was also found in reject stream. Most of the components of wood and paper and cardboard found in reject stream were large in particle size (>200 mm), heavy in weight/density or irregular in their shapes. In ferrous and non-ferrous metal streams a very small mass fraction of components (such as wooden pieces having iron/steel nail, light weight paper, soft plastic and foam) were found other than metals. These components might be in contact (in between or on top, etc.) with metals during magnetic and eddy current separation. Stream of heavy fraction mainly consisted of heavy particles of stone/rock, metal, long and hard pieces of wood and hard plastic. Stream of fine fraction mainly contained inert components (especially sand, gypsum and glass particles) and a relatively small mass fraction of other components (such as wood, paper and cardboard and foam) shredded to smaller particle size (<15 mm) during primary shredding of input waste material. Composition of the process streams taken from MT waste sorting plant to produce SRF from C&D waste is shown in Table 5.

The energy based composition of SRF produced from C&D waste was calculated from its composition (on mass basis) and net calorific values of the respective components (Nasrullah et al., 2014). This was calculated by multiplying the mass fraction of components of SRF with their respective net calorific values. The energy based composition of SRF produced from C&D waste is given in Fig. 4.

The major portion of energy in this SRF produced from C&D waste contained by wood, plastics (soft and hard) and paper and cardboard respectively. A high fraction of energy of this SRF belonged with wood component.

Carbon dioxide (CO_2, fossil) emission factor for SRF depends on its composition (i.e. share) of biomass and fossil carbon in it. Based on carbon content (C), bio carbon content (C_{bio}), moisture content and heating value (a.r.) of this SRF produced from C&D waste the carbon dioxide emissions (tCO_2/TJ) were calculated by using Eq. (1).

$$P_{CO2} = 1000 * 3.664 * C_{fos,ar}/H_{ar} \quad (1)$$

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

$$P_{CO2} = 28.3\ tCO_2/TJ$$

Table 5
Composition of various process streams produced in MT waste sorting plant to produce SRF from C&D waste (wet basis).

Component	C&DW[a] (wt%)	SRF (wt%)	Reject material (wt%)	Ferrous metal (wt%)	Non-ferrous metal (wt%)	Heavy fraction (wt%)	Fine fraction (wt%)
Paper and cardboard	12.0	22.0	6.0	0.6	0.4	1.2	1.6
Plastic (hard)	6.0	9.2	7.4	0.2	1.2	6.8	0.3
Plastic (soft)	3.6	6.8	1.2	–	0.4	–	0.6
Textile	3.8	6.0	3.4	0.2	0.6	–	0.6
Wood	23.6	38.0	12.6	1.4	0.8	14.0	2.8
Rubber	4.8	2.4	15.0	–	1.0	4.0	–
Metal	10.0	2.0	3.0	92.0	90.0	6.0	0.8
Foam	2.0	0.5	1.8	–	–	–	1.6
Glass	3.4	0.6	11.6	–	–	–	10.0
Building material[b]	14.2	1.5	22.0	2.6	2.0	64.0	58.0
Fines	16.6	11.0	16.0	3.0	3.6	4.0	20.5

[a] C&DW refers to C&D waste (i.e. input waste stream) and its composition was determined after primary shredding.

[b] Building material refers to stone/rock, concrete and gypsum, etc.

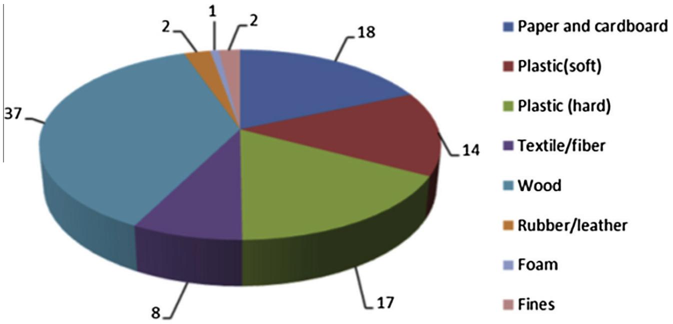

Fig. 4. Energy based composition of SRF produced from C&D waste.

where P_{CO2} is quantity of CO_2 (tCO_2/MJ), C_{fos}, is carbon (fossil) content, C is total carbon content, C_{bio} is carbon (biomass) content, *W* is moisture content and *H* is heating value (see Table 3).

Carbon dioxide (CO_2, fossil) emissions calculated for this SRF produced from C&D waste was 28.3 tCO_2/TJ.

5. Material balances

Mass flow of input waste's components in the output streams of SRF production plant was analyzed in terms of material balances. Material balances included the mass balance for paper and cardboard, wood, plastic (soft), plastic (hard), textile and rubber in the streams of this SRF production process. Material balances were calculated from (mass based composition) of input and output streams and mass flow balance in process streams of SRF production process. Mass of each component in every stream was calculated by multiplying the fraction of that component in the stream (see Section 4) with the total mass of that stream (see Section 3.1.1).

The mass flow of input waste's components in the various output streams (i.e. separation in various streams) of SRF production plant was based on their particle size distribution, weight/density, ferrous/non-ferrous properties and near-infrared (NIR)/specific spectral properties. Loss values was the difference of quantity (mass) between calculated mass of component in the input material stream and sum of mass of that component in the output streams and not found refers to a very minor amount of component (negligible) or it is not there in the streams. Material balances of input waste's (i.e. C&D waste) components: paper and cardboard, wood, plastic (soft), plastic (hard), textile and rubber in the output streams of SRF production plant are shown in Fig. 5.

Mass fraction of plastic (soft), paper and cardboard and wood recovered in the SRF stream was 84%, 82% and 72% respectively of their total input masses to MT plant. Higher mass recovery of plastic (soft) as compared with other input waste's components in SRF has been reported in literature (Nasrullah et al., 2014). A noticeable mass fraction of components (paper and cardboard and wood) was also found in the reject stream, being combustibles these components were not supposed to be in rejects but in SRF stream. In manual sorting of the process streams it was observed that the particles of wood and paper and cardboard found in reject stream were either large in their particle size (>200 mm) or irregular in their shapes. Material ending up in the reject stream after being passed from unit operations (i.e. wind shifter and near-infrared (NIR) sorting unit). It was observed that large particle size (heavy in weight) or irregular shapes of the combustible particles (wood and paper and cardboard) might be the reason for not being sorted/picked out by unit operations such as wind shifter and near-infrared (NIR) sorting unit. In order to optimize the sorting effect the shape of the material is important and range of the size distribution of particles has to be limited (Rotter et al., 2004).

More plastic (soft) was recovered in the SRF stream than plastics (hard). Mass fraction of plastic (soft) and plastic (hard) recovered in the SRF stream of their total input masses was 84% and 68% respectively. A considerable portion of plastics (hard) was found in the reject stream. Most of the components of plastic (hard) found in reject stream were PVC-plastic. Mass fraction of textile recovered in SRF stream was 70% and found in reject stream was 16% of its total input mass. Major portion of rubber material was found

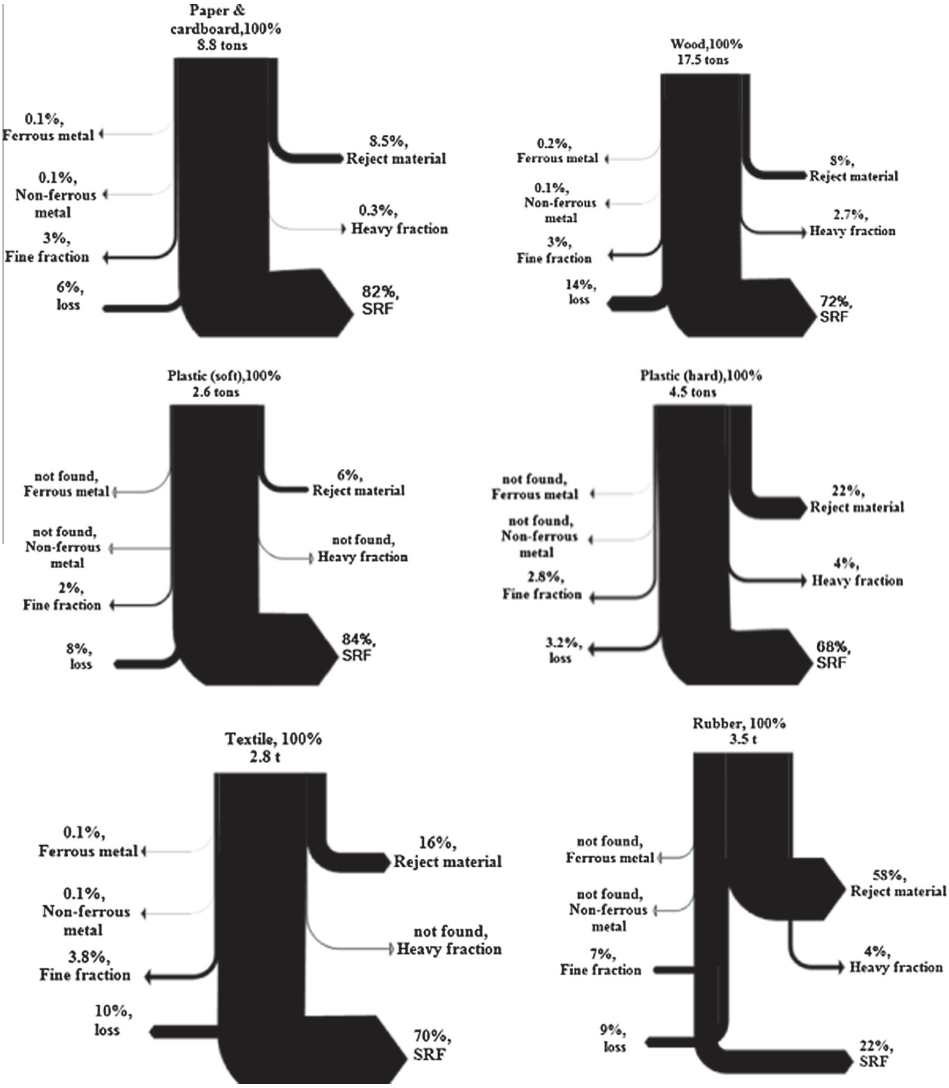

Fig. 5. Material balances of input waste components for SRF production process produced from construction and demolition waste (wet basis).

in the reject stream. Of the total input of rubber material to waste sorting process 58% was found in the reject stream. Rubber material found in reject stream was found to be highly chlorinated. In this MT process to produce SRF, sorting of highly chlorinated waste components (such as PVC-plastic and rubber material) was performed by NIR sorting technology. In order to provide high quality SRF near-infrared (NIR) technology reduces the chlorine content of SRF (Glorious, 2012).

After analysing the material balances of this MT process, it is observed that mass fraction of combustible material especially wood and paper and cardboard can be minimized in the reject stream through better primary shredding (by controlling the particle size distribution) of the input waste stream. This can increase the yield of SRF stream by making it more enriched with components of wood and paper and cardboard.

6. Conclusion

Production of SRF from the fraction of C&D waste which is relatively complicated and economically not feasible to sort out for recycling, recovered a very high portion of useful material in the form of SRF to be utilized for energy recovery. Of the total input C&D waste material to MT waste sorting plant to produce SRF, 44% material was recovered in the form of SRF and 6% in the form of recyclables (i.e. metals). In terms of energy recovery from this process, of the total input energy content of C&D waste material to MT plant 74% energy was recovered in the form of SRF.

Energy consumed in processing the C&D waste to produce SRF through MT was calculated in terms of inplant operations and outplant operations. For this specific process energy consumed on outplant operations was two times the energy consumed on inplant operations.

In composition of C&D waste, building material (such as stone/rock, concrete, gypsum material and concrete/sand particles) and wood were the major components. The mass fraction of building material along with fines was 30.8% and that of wood was 23.6% in the composition of C&D waste (wet basis). The SRF produced from C&D waste was enriched with wood, paper and cardboard and plastics. Mass fraction of wood, paper and cardboard and plastics (soft and hard) in the SRF was 38%, 22% and 16% respectively of tis composition. Stream of reject material produced in this process mainly contained inert material components (such as glass, stone/rock, fines), plastic (PVC-plastic) and rubber material (highly chlorinated).

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PAPER IV

Elemental balance of SRF production process: Solid recovered fuel produced from construction and demolition waste

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Elemental balance of SRF production process: Solid recovered fuel produced from construction and demolition waste

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HIGHLIGHTS

- Elemental balance of full scale SRF production is established.
- Mass flow of pollutant and potentially toxic elements in SRF production is examined.
- Source of pollutant and potentially toxic elements in waste components is identified.

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ABSTRACT

Quality of solid recovered fuel (SRF) demands that the waste components containing pollutant and potentially toxic elements (PTEs) and inert components are sorted out into separate small streams and to concentrate the suitable components into a prepared depolluted combustible fraction stream of SRF. In the SRF production, mass flow of waste components' type into the output streams determine the quality of SRF. This paper presents the mass flow of pollutant and potentially toxic elements in full-scale SRF production. The SRF was produced from construction and demolition waste (C&DW) through mechanical treatment (MT). The input and output streams of SRF production were chemically characterised for the concentration of inorganic elements in details. The results showed that of the total input chlorine content to the process, 34% was found in SRF and 48% in reject material. Mercury (Hg) and arsenic (As) were found concentrated in fine fraction i.e. of the total input content of mercury and arsenic, 64% and 42% respectively was found in fine fraction. Most of the lead (Pb) was found in reject material and fine fraction i.e. of the total input lead content, 45% and 44% was found in reject material and fine fraction respectively. In case of cadmium (Cd), of the total input content of cadmium, 68% was found in SRF. Among the components of C&D waste, rubber and plastic (hard) were measured to contain higher chlorine (Cl) content i.e. 7.6 wt.%, d. and 7.0 wt.%, d. respectively. Plastic (hard) was measured to contain 880 mg/kg, d. of lead (Pb) which was higher than measured in other components. Textile was measured to contain 12 mg/kg, d. of arsenic (As) which was higher than measured in other components.

1. Introduction

Solid recovered fuel (SRF) is becoming a significant contributor to the international resource and energy efficiency agenda [1,2]. To save primary fuels, energy intensive industries look for alternative fuels. With the utilization of SRF, renewable energy is recovered from the biogenic fraction of non-hazardous waste, and replaces fossil fuels in energy-intensive industries [3]. In Europe, SRF is mainly used in cement kilns, coal fired power plants and combined heat and power (CHP) plants [4–6]. The estimated possible use of SRF in long run (EU 27 2020) is 24–43 Mt/year [7]. Cement and lime producing industries as well as the coal fired power plants are interested in SRF having homogenous composition with guaranteed quality and availability [8]. Market security for SRF is based on producing a fuel having suitable and consistent quality [9–12]. In past production of refuse-derived fuel (RDF) in Europe struggled and could not create sufficient demand in market due to high concentration of chlorine and heavy metals in the fuel product [13]. The SRF has been introduced to distinguish it from classical RDF in terms of environmental and process-relevant quality standards [9,10,14].

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Concentration of elements in the output streams produced in SRF production [15,16] is directly linked with the sorting of input waste stream's components in the output streams [17]. In order to produce SRF with specified quality (in terms of heating value, moisture content and elemental concentration), it is important to understand the flow of waste components (paper, plastic, wood, textile, rubber) in the output streams of SRF production. SRF/RDF production technology (in terms of use and performance of unit operations) plays a vital role in defining the quality of recovered fuel [13,18,19].

In the EU waste strategy, construction and demolition waste (C&D waste) is considered as ''priority'' waste stream [20]. Environmental problems caused by C&D waste is not only due to its increased volume, but also from its treatment [21]. The previous research presented [16] that in Finland, non-recyclable fraction of C&D waste contains significant mass fraction of combustibles (wood, plastic, paper and cardboard and textile) which can be used for energy recovery in the form of SRF. In Finland, C&D waste contains more combustibles (especially wood) as compared to central Europe. In Finland, fraction of C&D waste which is complicated/not feasible for material recycling is being utilized to produce SRF through mechanical treatment. SRF produced from C&D waste was reported [16] to have net calorific value of 18.0 MJ/kg, a.r.

A comprehensive elemental analysis of the input and output streams and waste components of SRF production provides better understandings of the elemental quality of SRF and the link between SRF quality and flow of types of components in SRF production [17]. Very limited published research [13,17] is available which describe the elemental analysis/chemical characterisation of input and output streams and waste components produced in SRF/RDF production. Especially, there is hardly a published study available which describes the production of SRF from construction and demolition waste (C&DW) in the said context.

The objective of this paper is to analyse and examine in details, the mass flow of pollutant and potentially toxic elements (PTEs) in a full-scale SRF production produced from C&D waste. The input and output streams and waste components produced in SRF production are comprehensively chemically characterised for the concentration of inorganic elements. The elemental quality of the output streams of SRF production is understood by evaluating the elemental analysis of waste components and their mass flow in the output streams. Among the waste components, the potential source of pollutant and potentially toxic elements (PTEs) are identified based on their elemental analysis. The SRF was produced from the fraction of construction and demolition waste (C&DW) which was complicated/not feasible for recycling in a mechanical treatment (MT) plant using modern near-infra red (NIR) sorting technique.

2. Materials and methods

In a commercial scale experimental campaign, SRF was produced from C&D waste through mechanical treatment (MT). A batch of 74 tonnes of C&D waste was collected from the Metropolitan area of Helsinki region to produce SRF. In MT SRF production plant, input waste stream of C&D waste was further divided into different output streams; SRF, ferrous metal, non-ferrous metal, fine fraction, heavy fraction and reject material [16]. The sampling of process streams and their further treatment of sample preparation for laboratory analysis was performed by using CEN standard methods for SRF [22,23].

The MT based SRF production plant consisted of various unit operations/sorting techniques; primary shredding, screening (jigging and drum screens), metal separation (magnetic/eddy current separators), air classifiers, near-infra red (NIR) sorting units and secondary shredding. In order to produce SRF, the input waste stream of C&D waste passed through series of these unit operations. Components of input waste stream were classified into various output streams based on their material properties such particle size (screening), density/weight (air-classification), magnetic properties (magnetic/eddy-current separation) and infra-red/spectral properties (NIR sorting). The details of process description (in terms of unit operations used, their arrangement and functions in the process), standard methods used for the sampling of streams from SRF production plant and their sample preparation for laboratory analysis were presented in the previous research [15].

The elements investigated for their balance in SRF production were; chlorine (Cl), arsenic (As), cadmium (Cd), lead (Pb) and mercury (Hg). These elements were reported [17] as pollutant and potentially toxic elements in SRF production. In the refuse derived fuel (RDF) production chlorine, lead and cadmium were reported [16] often found to get concentrated in the fuel product. The elemental balance of SRF production process was based on the elemental analysis of the output streams produced in the process and was calculated by applying material flow analysis (MFA) approach. Methodology on MFA was reported [24,25] in details. The SRF production process evaluated to establish elemental balance by using MFA is shown in Fig. 1. The incoming waste material stream (i.e. C&D waste) was subjected to mechanical separation to produce SRF. The process involved only the mechanical separation of the input waste stream and not accumulate/store any material in it. Based on the law of mass conservation; the input mass balance of element (s) was calculated from sum of its mass in the output streams. Metals of each stream were not included in the elemental balance.

Elemental balance of input waste stream was calculated from the sum of mass of element in the output streams by using Eq. (1).

$$X_{\mathrm{input}}(s) = M_{\mathrm{input}} * C_{\mathrm{input}}(s) = \sum_{i=1}^{k} M_{\mathrm{pi}} * C_{\mathrm{pi}} \tag{1}$$

where X is the load; c is the concentration; M refers to the mass of stream; pi refers to the output i; (s) refers to the element; and k number of outputs.

Elemental analysis of the input and output streams and waste components of SRF production produced from C&D waste was performed in the laboratory. Elemental analysis included; halogen, heavy metal and major/minor/trace elements. Input and output streams analysed for their elemental analysis were; C&D waste, SRF, reject material, fine fraction and heavy fraction. The waste components analysed for their elemental analysis were; paper & cardboard, plastic (hard), plastic (soft), textile, rubber, foam and wood. The standard analysis methods used in laboratory for the elemental analysis of streams and waste components were briefly described in the previous study [17].

Specific load of elements contributed by waste components in unsorted waste stream of C&D waste was determined based on the composition of C&D waste [16] and elemental analysis of waste components (see Table 1). The specific load of elements was calculated by multiplying the mass fraction of component in C&D waste stream with the concentration of element in the component.

The uncertainty/sampling error determination in sampling (sampling of streams from SRF production plant) and sub-sampling (sample preparation of process streams for laboratory analysis) required very extensive sampling quantities (in terms of amounts of samples) which were not feasible for the sampling and subsampling of all the process streams (input and output) at this research scale. The issues related with the precision determination of sampling and sub-sampling methods for SRF were presented in details in QUOVADIS document [26]. The confidence level of measured and calculated values (for elemental

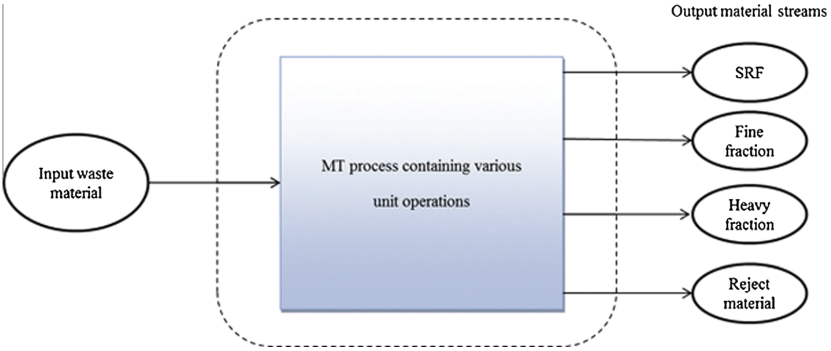

Fig. 1. Flow balance of MT process to produce SRF.

Table 1
Elemental analysis of components of construction and demolition waste (mean value of three laboratory sub-samples test).

#	Element	Unit	Paper & cardboard	Plastic (hard)	Plastic (soft)	Textile	Rubber	Foam	Wood
1	Cl	wt.%, d	0.3	7.0	0.18	3.8	7.6	0.32	0.037
2	F	wt.%, d	0.004	0.013	0.006	0.006	0.006	0.003	0.001
3	Br	wt.%, d	0.001	0.003	0.001	0.001	0.001	0.013	0.0002
4	Na	mg/kg, d	1700	1695	3400	3500	1200	2600	330
5	K	mg/kg, d	1000	1600	3400	3100	1500	2500	430
6	Mn	mg/kg, d	57	68	130	120	97	140	82
7	Cr	mg/kg, d	15	290	72	960	110	45	3.3
8	Cu	mg/kg, d	36	33	41	76	2300	49	3.1
9	Ni	mg/kg, d	7.0	62	32	19	91	15	1.7
10	Zn	mg/kg, d	93	890	300	460	2100	190	61
11	Sb	mg/kg, d	4.2	240	4.0	85	190	220	0.5
12	As	mg/kg, d	0.8	2.0	2.6	12	1.4	1.4	0.5
13	Cd	mg/kg, d	0.15	1.5	0.2	1.3	5.2	0.12	0.12
14	Co	mg/kg, d	1.5	4.0	5.0	4.8	4.8	4.1	0.5
15	Pb	mg/kg, d	26	880	72	450	100	15	5.4
16	Mo	mg/kg, d	2.3	15	2.3	3.0	2.4	1.0	0.5
17	Se	mg/kg, d	0.95	0.7	0.85	0.59	0.5	0.75	0.5
18	Tl	mg/kg, d	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
19	V	mg/kg, d	4.5	160	14	14	21	18	0.8
20	Hg	mg/kg, d	0.1	0.05	0.2	0.2	0.05	0.1	0.02

analysis of waste components, specific load contribution calculations and elemental balances in SRF production) for this research work is based on the fact that the sampling of streams from SRF production plant and their sample preparation for laboratory analysis were performed by using CEN standard methods for SRF [22,23].

3. Results and discussions

3.1. Elemental analysis of components of input waste stream (C&D waste)

The elemental analysis of components of C&D waste (i.e. input waste stream) facilitated the identification of potential source waste components for pollutant, hazardous and potentially toxic elements. The elemental analysis of components of input waste stream (C&D waste) is given in Table 1.

Among the components of C&D waste, rubber, plastic (hard) and textile were identified as potential sources of chlorine (Cl). Rubber, plastic (hard) and textile were measured in the laboratory to contain 7.6 wt.%, 7.0 wt.% and 3.8 wt.% respectively of chlorine (on dry basis). Among the waste components plastic and rubber material were reported in literature [27,28] to contain higher chlorine content. Paper and cardboard were also measured to contain noticeable chlorine content i.e. 0.3 wt.%. In literature [29–31] paper and card are reported to contain total chlorine content up to 0.5 wt.%. As compared with the other waste components of C&D waste, rubber material was also measured to contain higher content of copper (Cu) i.e. 2300 mg/kg (dry basis). Rubber and plastic (hard) were measured to contain high content of zinc (Zn) i.e. 2100 mg/kg and 890 mg/kg respectively (dry basis). In a previous study [17] among the waste components of commercial and industrial waste (C&IW) rubber material was reported as a potential source of copper (Cu) and zinc (Zn) elements. Researchers reported [32,33] rubber in municipal solid waste (MSW) containing high zinc content and rubber as a source of zinc. Other components measured to contain noticeable content of zinc were textile and plastic (soft). Higher content of antimony (Sb) was measured in plastic (hard) and foam material as compared with the other waste components of C&D waste. In textile content of arsenic (As) measured was 12 mg/kg (dry basis) which was higher than measured in other waste components of input waste stream. In plastic (hard) content of lead (Pb) measured was 880 mg/kg (dry basis) which was higher than measured in other waste components of input waste stream of C&D waste. Components of C&D waste are shown in Fig. 2.

The specific load of various elements in unsorted waste stream of C&D waste was determined based on the composition of C&D waste [16] and elemental analysis of components of C&D waste

Paper and cardboard Plastic (hard)

Plastic (soft) Textile

Rubber Foam

Wood

Fig. 2. Components of construction and demolition waste.

(see Table 1). The specific load calculation was based on both the parameters; the concentration of element in waste component and mass fraction of waste component in input waste stream (described in Section 2).

Major load of chlorine (Cl) in unsorted C&D waste was contributed by plastic (hard) and rubber components. Of the total chlorine load in unsorted C&D waste 42% and 37% (dry basis) was contributed by plastic (hard) and rubber components respectively. Textile was also found to carry about 14% of the total load of chlorine in C&D waste. Researchers have reported [11,17,34] the dominance of plastics as contributor of chlorine load in the SRF. The concentration of bromine (Br) in foam material was measured as 0.013 wt.% which was higher than measured in other waste components. Specific load of bromine (Br) in input waste stream

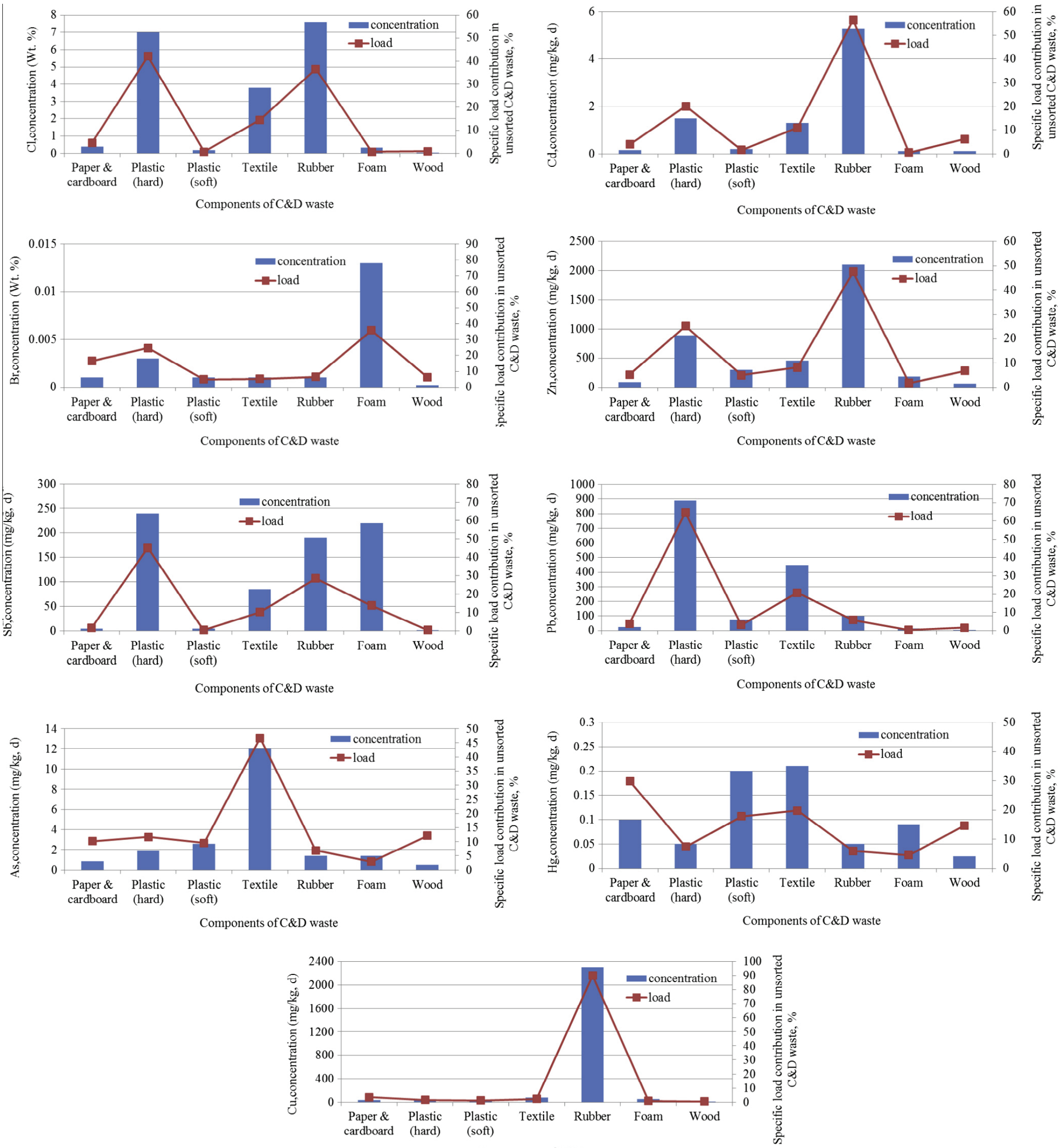

Fig. 3. Concentration of various elements in waste components and their specific load contribution in unsorted construction and demolition waste.

(C&D waste) was mainly contributed from foam material. In unsorted C&D waste, load of antimony (Sb) was mainly influenced by plastic (hard) and rubber components i.e. 47% and 27% respectively. The specific load of arsenic (As) in unsorted C&D waste was contributed exclusively by textile component i.e. about 48% of the total load. In case of load of cadmium (Cd), zinc (Zn) and copper (Cu), rubber material contributed 57%, 48% and 90% respectively of their total respective loads in unsorted C&D waste. Especially, a very high load (i.e. 90%) of copper was contributed by rubber material due to high concentration of copper in rubber and a considerable mass fraction of rubber in input waste stream of C&D waste. The results having high specific load contribution of copper, zinc and cadmium by rubber material in unsorted C&D waste stream are in agreement with the previous study made for C&IW [17]. Plastic (hard) was found to carry 20% and 25% of the total loads of cadmium and zinc respectively in C&D waste. The load of lead (Pb) in input waste stream of C&D waste was mainly influenced by plastic (hard) i.e. 65% of the total load. In contrast to other elements the load of mercury (Hg) in unsorted C&D waste was relatively uniformly distributed among paper & cardboard, plastic (soft) and textile. Concentration of various elements in waste components of C&D waste and their elemental specific load in unsorted C&D waste is shown in Fig. 3.

The determination of elemental analysis of waste components and their elemental specific load in unsorted C&D waste facilitated to trace and identify the potential source material (i.e. waste components) containing pollutant and potentially toxic elements. Among the waste components of C&D waste, rubber, plastic (hard) and textile were identified as the most critical components in defining the presence of pollutant and potentially toxic elements in the various output streams produced in SRF production.

3.2. Elemental balances of SRF production produced from C&D waste

Based on the elemental analysis of process streams (output streams) the elemental balance of SRF production process was established by using MFA approach (see Section 2.). The elemental analysis of input and output streams of SRF production process produced from C&D waste is given in Table 2. The elemental balance of SRF production facilitated to examine the mass flow of pollutant and potentially toxic elements (PTEs) from input waste stream of C&D waste to the output streams of SRF production. The elements investigated for their elemental balance were; chlorine (Cl), arsenic (As), cadmium (Cd), lead (Pb) and mercury (Hg). In the SRF production process produced from C&D waste, chlorine and lead were found to get concentrated in reject material, arsenic and mercury in fine fraction and cadmium in the SRF.

Sorting processes in SRF production plant are designed based on material properties e.g. particle size (screening), density/weight (air classifier), magnetic properties (magnetic separation), infra-red (IR) – spectral properties (NIR sorting). The concentration of elements in the output streams was directly linked with the type of waste components sorted in those streams. Stream of reject material was measured to contain higher chlorine content as compared with the other output streams in the SRF production. This was due to the high mass fraction of plastic (hard) and rubber material in the reject stream. In the previous study [16], it was found that major fraction of plastic (hard) in the reject stream contained PVC-plastic. The reject material stream was also measured to contain 490 mg/kg, d. of lead (Pb) content which was higher than measured in other output streams, this could be due to the considerable mass fraction of plastic (hard) and textile components in reject material stream as these components were measured to contain high concentration of lead (see Table 1) than other waste components. In the elemental balance, of the calculated total input concentration of chlorine (Cl) and lead (Pb) to the process, 48% and 45% respectively was found in the reject material stream. The use of near-infrared (NIR) sorting technology in the SRF production facility was very useful in directing away the highly chlorinated plastic and rubber components from SRF into reject material. NIR technology is capable of reducing the chlorine content of the SRF and is commonly used in newly built SRF producing mechanical biological treatment (MBT) plants [8,11,35]. Of the total input chlorine content to the process, 34% was found in the SRF stream. The chlorine content in the SRF was measured as 0.4 wt.% (dry basis). Sorting of plastic (especially PVC-plastic) and highly chlorinated rubber material into reject material and high recovery of wood, paper and cardboard and plastic (soft) in the SRF stream [16] effectively reduced the chlorine content of SRF.

Stream of fine fraction was measured to contain higher concentration of arsenic (As) and mercury (Hg) as compared with the other output streams. The mercury content in fine fraction stream was measured as high as 0.7 mg/kg (dry basis). In the elemental balance, of the calculated total input concentration of mercury (Hg) and arsenic (As) to the process, 64% and 42% respectively was found in the fine fraction stream. Higher mass flow of mercury (Hg) and arsenic (As) in the fine fraction stream could be linked with the fact that the waste components containing higher mercury and arsenic content were shredded (or were already smaller in size) to smaller particles (<15 mm) (during primary shredding)

Table 2
Elemental analysis of various streams produced in SRF production process: SRF produced from construction and demolition waste (mean value of three laboratory sub-samples test).

#	Element	Unit	Input waste (C&DW)	Reject material	Fine fraction	Heavy fraction	SRF
1	Cl	wt.%, d	0.6	2.2	0.2	1.0	0.4
2	F	wt.%, d	0.01	0.006	0.002	0.005	0.004
3	Br	wt.%, d	0.005	0.008	0.002	0.001	0.003
4	S	wt.%, d	0.7	0.7	2.8	0.3	0.3
5	Na	mg/kg, d	8370	8160	14,400	7955	1470
6	K	mg/kg, d	6120	8062	13,700	11,571	1078
7	Ca	mg/kg, d	58,050	56,625	100,800	46,284	17,150
8	Mg	mg/kg, d	5940	5916	8500	5152	1274
9	P	mg/kg, d	315	392	490	343	519
10	Al	mg/kg, d	18,090	24,280	37,500	30,012	4802
11	Si	mg/kg, d	51,660	45,008	46,700	3706	12,152
12	Fe	mg/kg, d	7560	10,330	18,200	11,842	1274
13	Ti	mg/kg, d	1530	2130	2400	316	1274
14	Cr	mg/kg, d	135	178	130	100	35
15	Cu	mg/kg, d	657	952	140	714	350
16	Mn	mg/kg, d	270	247	680	280	68
17	Ni	mg/kg, d	37.8	68	45	22.6	8.0
18	Zn	mg/kg, d	405	594	500	307	176
19	Sb	mg/kg, d	42.3	70	10.0	5.8	84
20	As	mg/kg, d	15.0	10	13.0	4.5	6.6
21	Ba	mg/kg, d	260	646	680	388	140
22	Cd	mg/kg, d	1.5	1.0	0.6	4.0	4.4
23	Co	mg/kg, d	6.0	16.0	11.0	5.0	2.8
24	Pb	mg/kg, d	135	490	380	208	42
25	Mo	mg/kg, d	4.8	5.0	4.3	1.2	1.5
26	Se	mg/kg, d	1.8	2.2	4.0	3.0	2.7
27	Tl	mg/kg, d	0.5	0.5	0.5	0.6	0.5
28	Sn	mg/kg, d	13.5	95.0	26	126	14.7
29	V	mg/kg, d	23.4	38.0	48	33.5	4.0
30	Hg	mg/kg, d	0.22	0.08	0.7	0.05	0.2

and screened out as fine fraction in the screening section of the process. Textile component of input waste stream (i.e. C&D waste) was measured to contain 0.2 mg/kg (dry basis) of mercury (Hg) content and 12 mg/kg (dry basis) of arsenic (As) content which were higher than measured in other components (see Table 1). Of the total input calculated mass of lead (Pb) to the process 45% and 44% was found in the reject material and fine fraction streams respectively. This high mass flow of lead in the reject material and fine fraction streams might be due to a significant mass fraction of glass components in both streams. A considerable mass fraction of plastic (hard) components in the reject stream could also have caused high mass flow of lead in the reject stream as plastic (hard) component was measured to contain higher lead (Pb) content than other components of input waste stream (see Table 1).

In case of cadmium (Cd), a higher mass flow of the input cadmium content was found in the SRF stream as compared with the other streams. Of the calculated total input concentration of cadmium to the process, 68% was found in the SRF stream. Among the waste components, rubber material was measured to contain 5.2 mg/kg, d. of cadmium (Cd) which was higher than measured in other components. In unsorted C&D waste, rubber material carried more than 50% load of cadmium. Other than rubber, plastic (hard) was calculated to carry 20% load of cadmium in unsorted C&D waste. Cadmium was reported to get concentrated

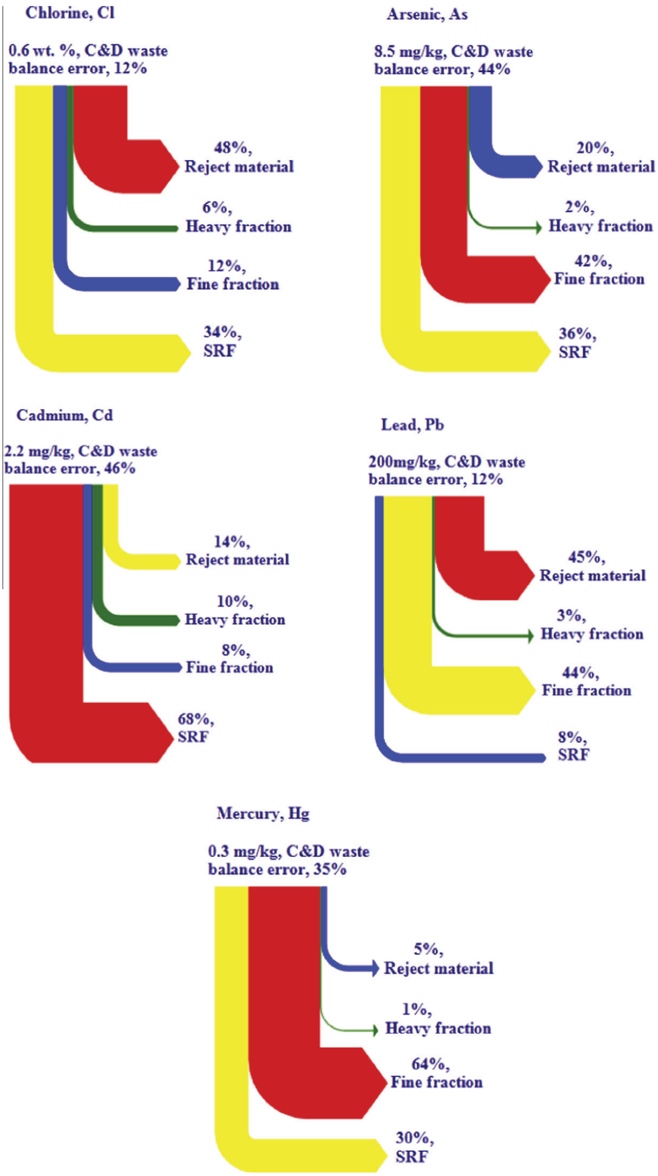

Fig. 4. Elemental balance of SRF production process: SRF produced from construction and demolition waste (C&DW).

Table 3
Qualitative classification of SRF produced from construction and demolition waste.

Classification property	Value	Class
Net calorific value (NCV)	18.0 MJ/kg (a.r)	3
Chlorine (Cl)	0.4% (dry)	2
Mercury (Hg)	0.009 Mg/MJ (a.r.)	1

in refuse derived fuel (RDF) product in spite of using various sorting techniques, and to reduce the cadmium concentration in RDF the development of waste sorting technique with the particular focus on the separation of goods containing cadmium was recommended by Rotter et al. [13]. Mass flow of arsenic (As) was relatively uniformly distributed as compared with other elements in the output streams of fine fraction, SRF and reject material. The difference in the measured and calculated values of the element concentration is calculated as balance error in %. Different colours in sankey diagrams indicate the intensity of polluted stream for example, red colour indicate the highest polluted stream after that yellow and blue colours respectively and green colour indicates the least polluted stream. Elemental balance of SRF production process: SRF produced from C&D waste through MT is shown in Fig. 4 in the form of sankey diagrams.

In the SRF production, high recovery of combustibles (especially paper and cardboard, wood and soft type plastics) in the SRF stream and sorting of PVC-plastic, highly chlorinated rubber material and other waste components containing hazardous chemical elements in the reject stream (through NIR sorting technology) effectively reduced the overall content of chlorine and other hazardous elements in the fuel product of SRF. In the previous study [15], it was observed that high moisture content (i.e. 25.6 wt.%) of input waste stream could be one of the reasons for combustibles (especially wood and paper and cardboard) to not get sorted (properly) by sorting processes (especially air classifier) and ended up in reject material instead of being recovered into SRF stream. Whereas, moisture content of C&D waste [16] was comparatively lesser (i.e. 14.0 wt.%) as compared with that of C&IW [15] and was observed to have comparatively better sorting (by air classifiers) in terms of putting more combustibles (especially wood and paper and cardboard) in the SRF stream. However, there was still a noticeable mass fraction of combustible components (wood and paper and cardboard) having large particle size (>250 mm) and irregular shape in the reject material stream [16]. Recovery of the said combustible components into SRF stream could have further enhanced the elemental quality (by effectively reducing the concentration of pollutanat and PTEs) and yield of the SRF.

The previous studies [15,16,36] described that better particle size distribution of input waste steam (in terms of particle size and shape) in primary shredding, steady mass flow of waste material passing through each unit operations and proper functioning of unit operations (especially air classifier and NIR sorting units in terms of regular maintenance checks) play key role in recovering maximum combustibles in the SRF from input waste stream. Based on the elemental analysis and specific elemental load of waste components (see Table 1 and Fig. 3), in the SRF production, directing away plastic (PVC-plastic), rubber and textile (to certain extent, especially synthetic textile components) from SRF stream and maximum recovery of paper and cardboard, wood and plastic (soft) into SRF stream effectively reduced the concentration of pollutant and potentially toxic elements (PTEs) in the SRF.

The SRF produced from C&D waste was classified as per CEN standards for SRF [37] based on limit values for three important fuel properties i.e. net calorific value (NCV, ar), chlorine content (%, dry) and mercury content (mg/MJ, ar). The qualitative classification of SRF produced from C&D waste is given in Table 3. Net calorific value (NCV, as received basis) of SRF produced from C&DW was measured as 18.0 MJ/kg, a.r. [16].

4. SRF quality requirements with user's point of view

Classification system [37] for SRF sets limits for certain parameters (heating value, Cl, Hg). Power plants and cement kilns are the major users of SRF. Typically, SRF users have limit values for certain parameters of SRF. Among those parameters, chlorine (Cl) content and calorific value are the most important ones. For co-combustion in fluidized bed boilers and gasification, the preferred value of chlorine (Cl) content in SRF is <0.6 wt.%, and in cement kilns <0.9 wt.% or <1.0 wt.% [38,39]. Preferred (limit) net calorific value (NCV) is >15 MJ/kg (as received basis). In Finland, for Lahti waste (SRF) gasification plant the design SRF fuel values are; lower heating value (LHV) 18–24 MJ/kg, dry basis, chlorine (Cl) <0.6 wt.%, dry basis, mercury (Hg) <0.1 mg/kg, dry basis, moisture content <30 wt.% and ash content <15 wt.% [40]. The boiler design is generally done with the fuel composition as basis and different kind of solutions are chosen for different kind of fuels. Chlorine (Cl) relates to corrosion risk (and fouling). It is hard to give limit value for some parameter (halogen and heavy metals), which would apply in general SRF based boiler design. Most of the heavy metals relate to formation of emissions (in flue gas and fly ash), but some like lead (Pb), zinc (Zn) and tin (Sn) also to boiler operation (e.g. corrosion risk, fouling).

5. Conclusion

Elemental quality of solid recovered fuel (SRF) produced from non-recyclable fraction of construction and demolition waste (C&D waste) was examined and evaluated in details. The SRF was found to contain high elemental quality in terms of containing low concentration of pollutant and potentially toxic elements (PTEs), especially chlorine (Cl). The SRF was produced through mechanical treatment (MT) based on modern/high-tech sorting technique such as near-infra red (NIR) technology.

Elemental quality of SRF was evaluated based on the elemental balance of industrial scale SRF production. In SRF production of the total input chlorine (Cl), most of it was found in reject material i.e. 48 wt.% and in SRF it was 34 wt.%. Major fraction of input mercury (Hg) was found in fine fraction i.e. 64 wt.% of the total input mercury (Hg) content. Most of the input lead (Pb) to the process was ended up in reject material and fine fraction i.e. 45 wt.% and 44 wt.% respectively. Higher mass flow of arsenic (As) was found in fine fraction i.e. 42 wt.% of the total input content as compared with found in other output streams. In case of cadmium (Cd), major fraction of it was found in the SRF i.e. 68 wt.% of the input cadmium (Cd) content. Unit operation with particular focus on the separation of cadmium containing waste components could be useful in order to reduce the cadmium content in SRF.

Among the waste components, plastic hard (PVC-plastic), rubber material and synthetic types of textile were found as potential source of pollutant and potentially toxic elements and were recommended to be directed away from fuel product (SRF). On the other hand, maximum recovery of paper and cardboard, wood and plastic (soft) was desired in order to enhance the elemental quality and yield of SRF.

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PAPER V

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

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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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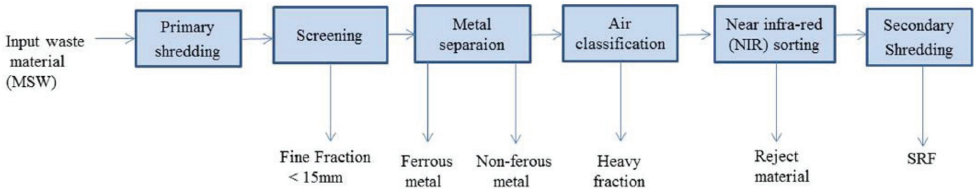

Figure 1. Simplified MT process to produce SRF from MSW.
MSW: municipal solid waste; SRF: solid recovered fuel.

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

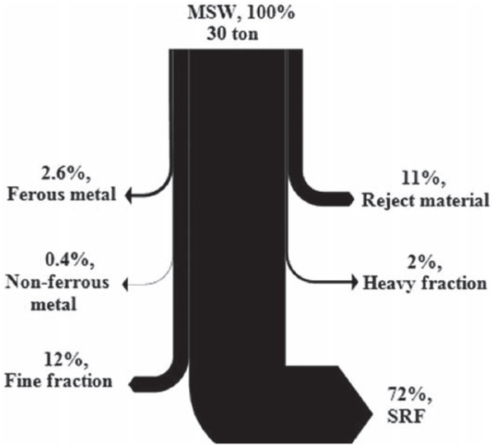

Figure 2. Mass flow balance in process streams of SRF production process: SRF produced from MSW (wet basis).
MSW: municipal solid waste; SRF: solid recovered fuel.

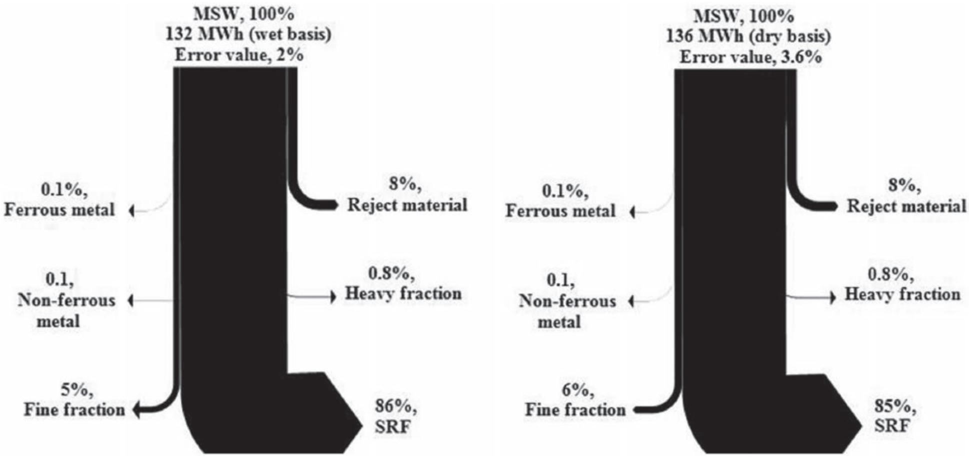

Figure 3. Energy flow balance in process streams of SRF production process: SRF produced from MSW.
MSW: municipal solid waste; SRF: solid recovered fuel.

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.

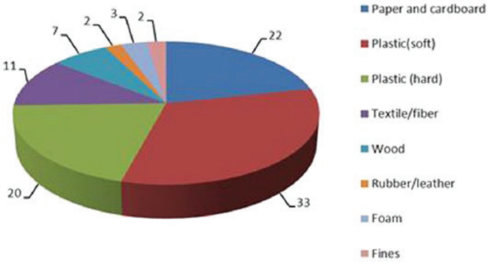

Figure 4. Energy (MJ kg-1, a.r.) based composition of SRF produced from MSW (energy waste collected from households).

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:

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

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

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):

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

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

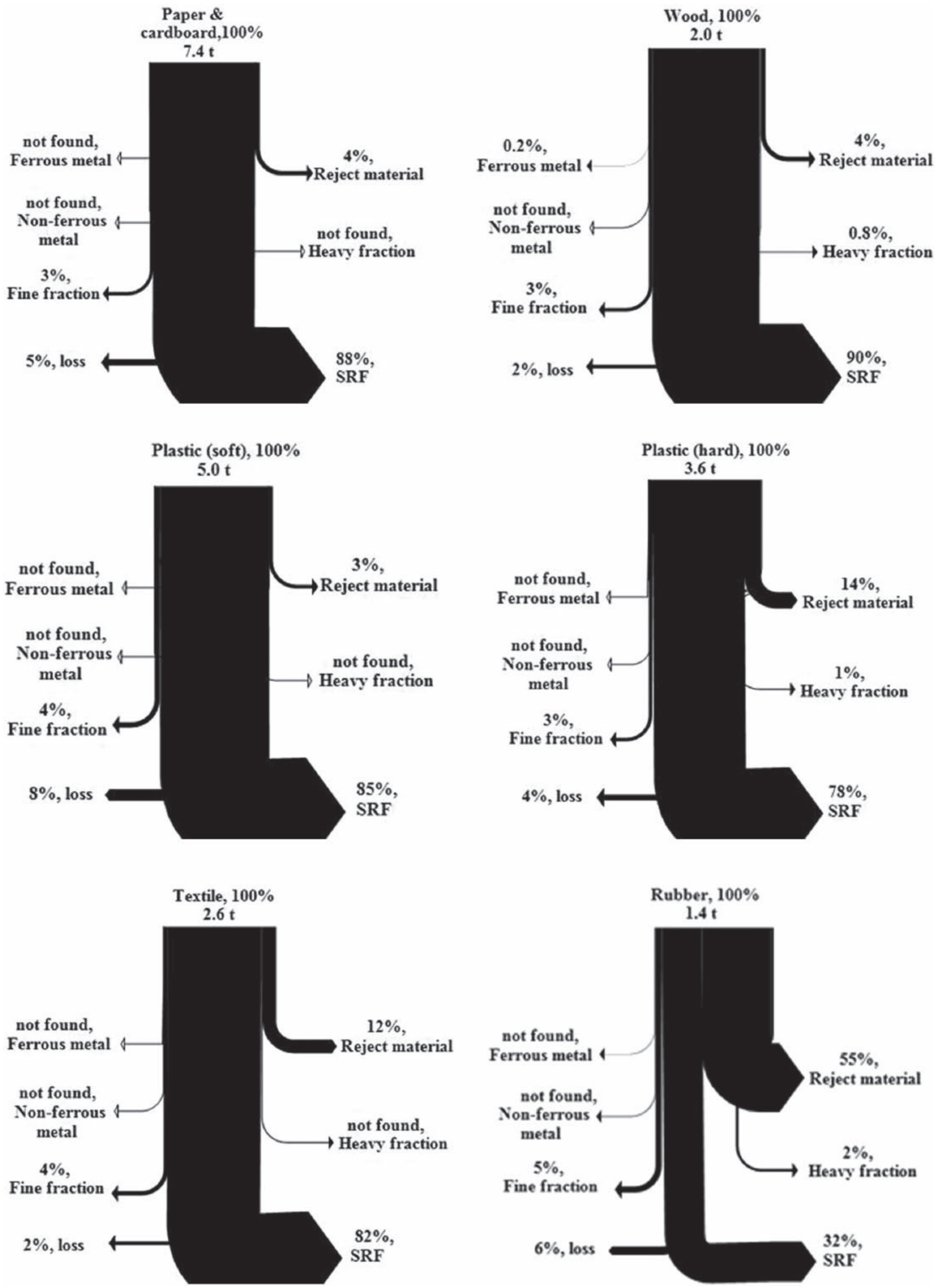

Figure 5. Material balances of input waste components in the output streams of SRF production plant produced from MSW (energy waste collected from households) (wet basis).
SRF: solid recovered fuel.

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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PAPER VI

Elemental balance of SRF production process: Solid recovered fuel produced from municipal solid waste

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Elemental balance of SRF production process: solid recovered fuel produced from municipal solid waste

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Abstract

In the production of solid recovered fuel (SRF), certain waste components have excessive influence on the quality of product. The proportion of rubber, plastic (hard) and certain textiles was found to be critical as to the elemental quality of SRF. The mass flow of rubber, plastic (hard) and textiles (to certain extent, especially synthetic textile) components in the output streams of SRF production was found to play the decisive role in defining the elemental quality of SRF. This paper presents the mass flow of polluting and potentially toxic elements (PTEs) in SRF production. The SRF was produced from municipal solid waste (MSW) through mechanical treatment (MT). The results showed that of the total input chlorine content to process, 55% was found in the SRF and 30% in reject material. Of the total input arsenic content, 30% was found in the SRF and 45% in fine fraction. In case of cadmium, lead and mercury, of their total input content to the process, 62%, 38% and 30%, respectively, was found in the SRF. Among the components of MSW, rubber material was identified as potential source of chlorine, containing 8.0 wt.% of chlorine. Plastic (hard) and textile components contained 1.6 and 1.1. wt.% of chlorine, respectively. Plastic (hard) contained higher lead and cadmium content compared with other waste components, i.e. 500 and 9.0 mg kg^{-1}, respectively.

Keywords

Solid recovered fuel, municipal solid waste, household energy waste, elemental balance, polluting and potentially toxic elements

Introduction

Solid recovered fuel (SRF) can be a practical and environmentally safe outlet for recovering value from the non-sustainably recyclable waste fraction (Velis and Copper, 2013), substituting fossil fuels (Beckmann et al., 2012; Thiel, 2007; Weber and Gehrmann, 2007). In comparison with pure disposal, the use of waste-derived material for recycling and energy recovery is a preferable waste management option in terms of climate change impact (Dehoust et al., 2010; Friege and Giegrich, 2008). In a new virtuous cycle, the potential of recovered fuels prepared form solid waste materials enforces us to consider their position in the emerging landscape of resource efficiency (Velis and Copper, 2013).

SRF is prepared from non-hazardous waste to be utilized for energy recovery in incineration/co-incineration plants and meeting the classification and specifications requirements laid down in European Committee for Standardisation (CEN) standards (EN 15359). SRF is a product of mechanical treatment (MT) or mechanical biological treatment (MBT) plants processing unrecyclable waste. Mechanical processing concentrates suitable waste components into a prepared combustible fraction stream of SRF, and separates out recyclables (metals), polluted (reject material and fine fraction streams containing comparatively higher concentration of polluting elements and PTEs than other output streams) and non-combustible waste components (inert such as stone/building material and glass etc.) into separate small streams (Nasrullah et al., 2014a, 2014b, 2015a). Quality and yield of SRF is affected by the type of input waste material and production technology (Nasrullah et al., 2013; Wilén et al., 2002). In Finland, SRF is currently produced from various types of waste streams such as commercial and industrial waste (C&IW), construction and demolition waste (C&DW) and municipal solid waste (MSW) in MT-based SRF production plants. The SRF is being utilized in cement kilns, lime kilns, coal-fired power plants and combined heat and power (CHP) plants for the production of

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energy (power and heat), reducing the amount of waste going to landfill and replacing the fossil fuels to a significant extent. Due to the developments in the field of waste-derived alternative fuels, the use of SRF as fuel/co-fuel has increased significantly in Finnish waste-to-energy technology, especially fluidized bed combustion and gasification could handle such fuel.

SRF referring to a fuel, meeting defined quality specifications, is a possible energy recovery option in industrial facilities (Rotter et al., 2011). The chlorine content in SRF is key to fuel quality because of the concern that high concentrations could severely increase ash deposition in the convective part of boilers (Wu et al., 2011). The European Committee for Standardisation (CEN) selected residual chlorine content as the key technical performance indicator of SRF quality (EN 15359). The composition of ash is affected by the trace and major elements in fuel (Konttinen et al., 2013). From an emission point of view, generally in SRF, concentration of heavy metals plays its part in defining that how 'clean' the SRFs are. Therefore, as general rule, concentration of heavy metals in SRF is to be kept low (Gawlika et al., 2007).

In MT/MBT plants, the quality and yield of SRF stream is directly linked with the proper sorting of input waste stream's components into the relevant output streams. The sorting of input waste stream's components into the relevant output streams is found significantly affected by their physical properties or appearance (e.g. particle size, shape, weight/density and moisture content of waste components) (Nasrullah et al., 2014a, 2014b, 2015a). In SRF production, the quality of SRF could be very well understood through a comprehensive elemental analysis of input and more importantly the output streams (Nasrullah et al., 2015b; Velis et al., 2013). There are very few published studies (Nasrullah et al., 2015a, 2015b; Rotter et al., 2004; Velis et al., 2013) that considered the chemical characterization and elemental flows in output streams of SRF/RDF production process. In particular, there are hardly any published studies available (Nasrullah et al., 2015a, 2015b) that describe the mass flow of polluting and potentially toxic elements (PTEs) and chemical characterization of the input and output streams of SRF production, and present the link between elemental concentration and mass flow of waste components from input to the output streams.

The objective of this paper is an in-depth examination and detailed evaluation of the mass flow of polluting elements and PTEs in SRF production. The SRF was produced from MSW through MT. This research work examined in detail the concentration of inorganic elements in the input and the output streams of SRF production. The link between SRF quality and mass flow of types of waste components in the output streams is presented here. In this paper also, the sources of polluting elements and PTEs are traced and identified.

Materials and methods

In an industrial-scale experimental campaign, SRF was produced from a batch of 30 tonnes of MSW. The stream of MSW used to produce SRF was household energy waste (fraction) collected from the metropolitan area of Helsinki region. This household energy waste stream was not subject to recycling but to energy recovery. Energy waste was source separated at the household level containing about 75 wt.% of energy-related waste components, for example paper and cardboard, plastics, textile, wood, rubber, foam material and a small proportion of non-energy waste components such as inert materials (metals, glass, stones) and food waste (Nasrullah et al., 2015a) due to false sorting.

In an SRF production plant, a series of unit operations was used, such as primary shredding, screening, magnetic/eddy current separation, air classifiers, near-infra-red (NIR) sorting units and secondary shredding, to sort/classify the input waste stream's components into the relevant output streams. The input waste stream was further divided/classified into various output streams of material, i.e. SRF, ferrous metal, non-ferrous metal, fine fraction, heavy fraction and reject material. Sorting of input waste components into the output streams was based on material properties, e.g. particle size (screening), density/weight (air classifier), magnetic properties (magnetic separation) and NIR spectra sorting. Input and output streams were sampled the from the SRF production plant according to standard sampling methods for SRF (EN 15442). Sampling of streams was performed by using the static lot method, static conveyor belt method and manual drop flow method (EN 15442). Sample preparation of streams for their laboratory analysis was performed according to standard sample preparation methods for SRF (EN 15443). According to EN 15443, the methods for particle size reduction and sample division (i.e. mass reduction) were used at each stage of sample preparation for laboratory analysis. Elemental analysis of process streams and waste components was performed by using standard analysis laboratory methods, which are briefly described in the previous study (Nasrullah et al., 2015b). The SRF production process, sampling of process streams and their sample preparation for laboratory analysis are described and published in detail in the previous study (Nasrullah et al., 2014a).

The composition of input and output streams of SRF production was determined and presented in the previous research (Nasrullah et al., 2015a). The input stream was MSW, i.e. household energy waste, and was source separated at the households. The composition of MSW (i.e. energy waste collected from households) is representative of the said waste stream in the metropolitan area of the Helsinki region. Waste material was collected through trucks/lorries from their respective collection locations. The composition of household energy waste may vary to a certain (small) extent with location compared with other cities of Finland. The composition of input and output streams of SRF production from MSW (household energy waste) is given in Table 1.

The mass balance of SRF production from MSW (household energy waste) described and presented (Nasrullah et al., 2015a) the flow/distribution of mass from the input waste stream into the output streams. In the SRF production, of the total input MSW household energy waste), 72 wt.% was recovered as SRF, 12 wt.% was separated as fine fraction, 11 wt.% as reject material, 2 wt.% as heavy fraction and 3 wt.% as metals (ferrous/non-ferrous). The

Table 1. Composition of process streams produced in SRF production from MSW (energy waste collected from households, wet basis of material) (Nasrullah et al., 2015a).

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
Textiles	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.

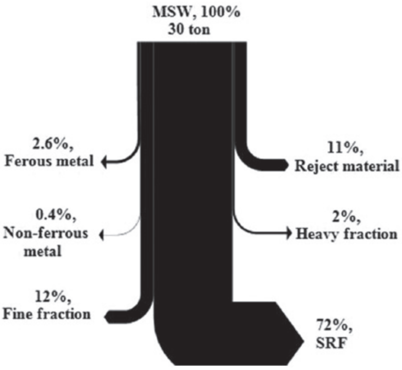

Figure 1. Mass flow balance in process streams of SRF production process: SRF produced from MSW (household energy waste, wet basis) (Nasrullah et al., 2015a). MSW, municipal solid waste; SRF, solid recovered fuel.

mass balance of SRF production from MSW (household energy waste) is shown in Figure 1.

In the process, the input waste material of MSW was subjected to mechanical separation/sorting only and no material transformation took place. Moreover, there is no material accumulation in the process and the input waste material was recovered in the form of output streams. In waste treatment processes, the whereabouts of hazardous chemicals can be determined only by an exact accounting of all substance flows (Rotter et al., 2004). The elemental balance of the SRF production process was calculated based on the elemental analysis of output streams (given in Table 3) produced in the process and material balance of SRF production (given in Figure 1). Based on the law of mass conservation; the input mass balance of element (*s*) was calculated from the sum of its mass in output streams. The total mass/concentration of element (*s*) in the output stream (*s*) was calculated by multiplying the concentration of element (*s*) in stream (given in Table 3) with total mass of stream (*s*) (given in Figure 1). The elemental balance calculations were performed according to material flow analysis (MFA) methodology by using Equation 1. The MFA methodology was described in detail (Bruner and Rechberger, 2004; Rechberger, 2001). The SRF production process evaluated to establish elemental balance by using MFA is shown in Figure 2. Configuration of the MT-based SRF production plant in terms of unit operations/sorting techniques used and their arrangement in the process have a profound effect on the outcome of the process. The mechanical processes and their functions that characterize the evaluated MT process are described and presented (Nasrullah et al., 2014a).

$$X_{input}(s) = M_{input} * C_{input}(s) = \sum_{i=1}^{k} M_{pi} * C_{pi}(s) \qquad (1)$$

where *X* is the load of element; *c* is the concentration of element; *M* refers to the mass of stream; P_i refers to the output $_i$; (*s*) refers to the element; and *k* number of outputs.

The specific load of various elements in unsorted input waste stream was determined based on the elemental analysis of waste components (Table 2) and composition of the input waste stream (Table 1). The specific load of an element in components of the input waste stream was calculated by multiplying the mass fraction of that component in the input waste stream with the concentration of element in that component. The sources of polluting elements and PTEs among the waste components of MSW were traced and identified based on the elemental analysis of waste components (Table 2).

Determination of the uncertainty aspects in sampling (sampling of streams from SRF production plant) and sub-sampling (sample preparation of streams for laboratory analysis) required very extensive sampling quantities, their treatment and analysis of all the streams (input and output), and was almost not feasible at this scale of research. The precision of the sampling and sub-sampling methods for SRF was presented in detail in QUOVADIS

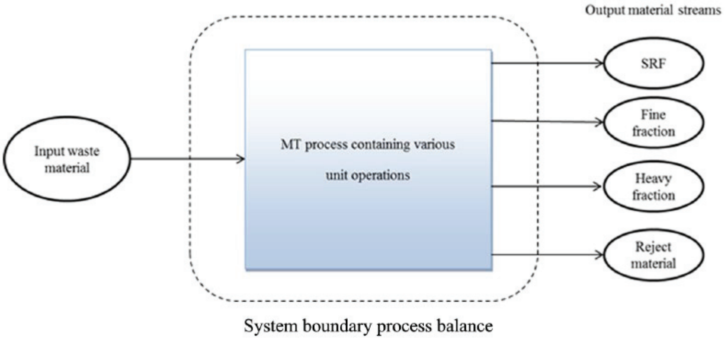

Figure 2. Flow balance of MT process to produce SRF. MT, mechanical treatment; SRF, solid recovered fuel.

Table 2. Elemental analysis of components of municipal solid waste (MSW) (energy waste collected from household) (mean value of three laboratory sub-samples test).

#	Element	Unit	Paper & cardboard	Plastic (hard)	Plastic (soft)	Textiles	Rubber	Foam	Wood	Food waste
1	Cl	wt.%, d	0.15	1.6	0.83	1.1	8.0	0.75	0.05	1.2
2	F	wt.%, d	0.002	0.003	0.004	0.004	0.001	<0.001	<0.001	0.002
3	Br	wt.%, d	0.001	0.001	0.001	0.008	0.001	0.001	0.001	0.001
4	Na	mg kg^{-1}, d	1400	570	1300	3700	980	800	220	11200
5	K	mg kg^{-1}, d	940	440	1200	1500	420	670	710	7600
6	Mn	mg kg^{-1}, d	32.0	25.0	37.0	42.0	30.0	25.0	49.0	58.0
7	Cr	mg kg^{-1}, d	15.0	67.0	41.0	5300	87.0	37.0	7.0	37.0
8	Cu	mg kg^{-1}, d	31.0	24.0	37.0	77.0	1400	40.0	4.7	140
9	Ni	mg kg^{-1}, d	6.0	26.0	18.0	31.0	32.0	17.0	3.3	14.0
10	Zn	mg kg^{-1}, d	47.0	170	160	310	3800	3800	20	110
11	Sb	mg kg^{-1}, d	3.0	56.0	5.0	62.0	170	2.8	1.8	3.4
12	As	mg kg^{-1}, d	0.43	0.61	1.0	2.4	0.6	0.5	0.1	0.8
13	Cd	mg kg^{-1}, d	1.2	9.0	0.50	3.1	1.5	0.5	0.12	0.1
14	Co	mg kg^{-1}, d	1.0	2.0	1.4	2.4	4.8	1.6	<0.5	1.4
15	Pb	mg kg^{-1}, d	12.0	500	19.0	63.0	370	38.0	3.0	120
16	Mo	mg kg^{-1}, d	0.9	1.6	21.0	4.0	2.2	1.3	0.5	1.8
17	Se	mg kg^{-1}, d	0.84	1.2	0.8	1.0	1.0	1.6	<0.53	1.1
18	Tl	mg kg^{-1}, d	<0.5	<0.5	<0.5	0.5	0.5	<0.5	<0.5	–
19	V	mg kg^{-1}, d	4.1	2.2	6.5	6.2	4.3	5.0	0.98	4.3
20	Hg	mg kg^{-1}, d	0.05	0.05	0.1	0.2	0.2	0.1	0.05	0.05

document (QUOVADIS). For this research work, the confidence in the measured and calculated values (for elemental analysis of waste components, specific load contribution calculations and elemental balances of SRF production) was based on the fact that the entire methodology of the research work was based on standards: CEN standard methods for SRF (EN 15442, EN 15443) and laboratory analysis methods (Nasrullah et al., 2015b).

Results and discussion

Elemental analysis of components of MSW

Among the waste components of MSW, rubber was found to be a major source of chlorine containing 8.0 wt.% of it. Rubber material also contained rubber shoes (rubber material contained various types of rubber components and rubber shoes were one of them). Among the components of waste, rubber was reported (Nasrullah et al., 2015b, 2015c) to contain higher concentration of chlorine. Among the components of SRF, rubber shoes were one of those reported to bear high chlorine content (Velis et al., 2012) and were recommended to be directed away from the SRF stream (Velis et al., 2013). Rubber material was also measured to contain higher copper (Cu) than other waste components. Components of rubber and foam were measured to contain considerably higher zinc (Zn) content compared with other waste components. Food waste in MSW was measured to contain 1.2 wt.% of chlorine. The chlorine content could be due to the salt containing food in the food waste components. Textiles were measured to contain higher concentration of bromine compared with other waste components. In textiles, flame retardant textiles were reported one of the potential source of bromine (Vainikka and Hupa, 2012; Vainikka et al., 2011; Wua et al., 2014). Plastic (hard) was measured to contain higher concentration of lead and cadmium than other components of input waste stream. In the previous studies (Nasrullah et al., 2015b, 2015c) and this study the components of hard plastic (PVC-plastic) and rubber were found to be potential sources of chlorine and textiles (synthetic and flame retardant) a source of bromine. In these studies (Nasrullah et al., 2015b, 2015c), the component of rubber was measured to contain a higher content of copper compared with other components of various waste streams. The elemental analysis of components of MSW is given in Table 2.

The specific elemental load contribution by waste components identified the specific waste components, which contributed to the high load of polluting elements and PTEs in unsorted MSW. The specific load calculations were based on the concentration of elements in the component and the mass fraction of the component in the unsorted stream of MSW. Concentrations of various elements in waste components of MSW and their elemental specific load contribution are shown in Figure 3.

In unsorted MSW, the major load of chlorine was contributed by rubber material and plastic (hard). Rubber and plastic (hard) carried 40% and 20%, respectively, of the chlorine load in MSW. This was due to the considerable mass fraction of plastic (hard) and rubber in MSW and high chlorine content in these components. In previous research (Nasrullah et al., 2015b, 2015c), components of rubber and plastic (hard) were found to carry most of the chlorine load in C&IW and C&D waste. In waste-derived fuel, plastics carried a higher load of chlorine (Rotter et al., 2004; Velis et al., 2012). Rubber was also found to carry a higher load of antimony, zinc and copper in unsorted MSW compared with other waste components. The load of bromine in MSW was mainly influenced by the textile component, i.e. 50% of the total bromine load. The textile component was also found to carry about 35% load of arsenic in the input waste stream. The higher loads of bromine (Br) and arsenic in MSW were due to their higher concentration in textiles compared with other components and considerable mass fraction of textiles in MSW. In textiles, flame retardant textile components were measured to contain high bromine (Br) concentration. Among the waste components, rubber, plastic (hard) and textiles carried a higher load of antimony in MSW, i.e. 38%, 32% and 25%, respectively. In the input waste stream, the load of lead and cadmium carried by plastic (hard) was 60% and 58%, respectively, of total load. Plastic (hard) carried exclusively higher loads of lead and cadmium in MSW compared with other components. Among the waste components, plastic (hard) was measured to contain higher concentrations of lead and cadmium (Table 2) and in MSW the mass fraction of plastic (hard) was 12% (Nasrullah et al., 2015a). The specific load of mercury in MSW was mainly carried by textiles and plastic (soft), i.e. about 50% of the total load. Among the waste components, rubber was measured to carry exclusively a high load of copper (Cu) in MSW, i.e. about 70% of the total load. The higher load of copper (Cu) carried by rubber compared with other waste components was reported in C&IW and C&D waste (Nasrullah et al., 2015b, 2015c).

Among the waste components of MSW, rubber, plastic (hard) and textiles (to a certain extent, especially the synthetic type) were identified as the most critical in terms of affecting the elemental quality of the SRF, and their distribution in the output streams was recommended to be watch/monitor out carefully. On the other hand, paper and cardboard, wood and plastic (soft) were identified as the least containing polluting elements, and PTE components and their maximum recovery in the SRF stream could enhance the yield and effectively reduce the concentration of polluting elements and PTEs in the SRF.

Elemental balance of SRF production from MSW

The mass flow of polluting elements and PTEs was examined from input waste stream into the output streams in terms of elemental balance of SRF production process. The elements investigated for their balance were: chlorine, arsenic, cadmium, lead and mercury. These elements were reported (Nasrullah et al., 2015b, 2015c) as polluting elements and PTEs, which might become concentrated in the SRF stream. In the RDF production test runs chlorine, lead and cadmium was reported (Rotter et al., 2004) to be found often concentrated in the fuel product. The elemental analysis of input and output streams of SRF production from MSW (energy waste collected from households) is given in Table 3.

In the SRF production process, higher mass flow of input chlorine and cadmium content was found in the SRF stream compared with other output streams, whereas higher mass flow of input arsenic and mercury content was found in the fine fraction stream compared with other output streams. Lead was found to be comparatively homogenously distributed among SRF, fine fraction and reject material streams. The elemental balance of SRF production from MSW (energy waste collected from household) is shown in Figure 4. The elemental balance (shown in Figure 4) was based on elemental analysis of output streams (Table 3) produced in SRF production and the material balance of the SRF production process (Figure 1), and was calculated by using an MFA approach (see section 2). The difference in the measured (laboratory measurement, Table 3) and calculated (calculated by using MFA method on output streams previously described, see section 2) values of the input element concentration is calculated as the balance error. Different colours in Sankey diagrams indicate the extent to which the stream is polluted, for example a red colour indicate the highest polluted stream, after that yellow and blue colours, respectively, and a green colour indicates the least polluted stream.

Among the unit operations in SRF production, the air classifier and NIR sorting units were the most influential and mainly responsible for determining the composition of the SRF stream and therefore the quality and yield of the SRF. The air classifier sorts the lightweight components (especially paper and cardboard, plastic, wood and textiles) and put them into the SRF stream, and the NIR sorting unit separates waste components based on their infra-red/spectral properties and sorts the combustibles (paper and cardboard, wood, non-PVC plastics and textiles

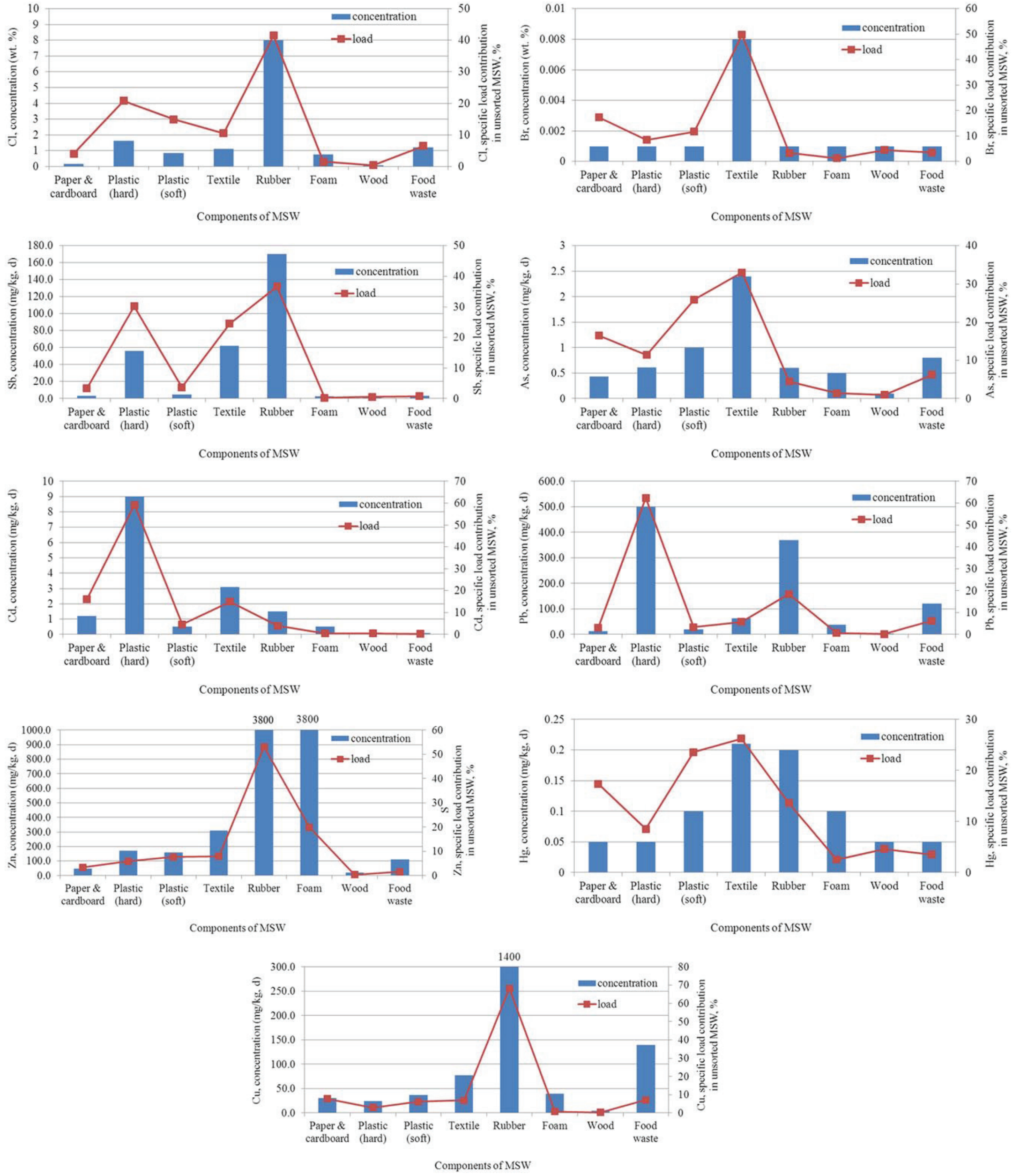

Figure 3. Concentrations and specific load contributions of individual elements to the waste components in unsorted MSW (energy waste collected from household). MSW, municipal solid waste.

etc.) into the SRF stream, whereas non-combustibles (especially high chlorinated rubber and plastics and inert, i.e. stones, metal etc.) ended up in the reject material stream. The mechanical process/unit operations used and their function in MT-based SRF production process are briefly discussed (see section 2) and presented in detail in the previous study (Nasrullah et al., 2014a).

The elemental analysis of components of input waste stream showed that rubber material and plastic (hard) components were potential sources of chlorine and to some extent textiles as well. In the case of cadmium, plastic (hard) measured to contain a higher cadmium content compared with other components of input waste stream. To some extent, the components containing high chlorine and cadmium content were not directed away from making their way into SRF stream. Even though the maximum mass fraction of input rubber and plastic (high chlorinated) was found in the reject material, there could still be certain

Table 3. Elemental analysis of various streams produced in solid recovered fuel (SRF) production from municipal solid waste (MSW; energy waste collected from households) (mean value of three laboratory sub-samples test).

#	Element	Unit	Input waste (MSW)	Reject material	Fine fraction	Heavy fraction	SRF
1	Cl	wt.%, d	1.5	2.7	1.1	0.04	0.6
2	F	wt.%, d	0.01	0.05	0.03	0.002	0.01
3	Br	wt.%, d	0.002	0.01	0.01	0.001	0.004
4	S	wt.%, d	0.2	0.5	1.0	0.1	0.2
5	Na	mg kg^{-1}, d	7918	9187	18 880	7112	1590
6	K	mg kg^{-1}, d	3530	4474	8496	13 872	924
7	Ca	mg kg^{-1}, d	30 623	36 604	56 262	82 356	28 925
8	Mg	mg kg^{-1}, d	2957	3142	6419	4566	1390
9	P	mg kg^{-1}, d	382	976	1227	307	338
10	Al	mg kg^{-1}, d	12 402	15 994	23 320	48 114	6262
11	Si	mg kg^{-1}, d	41 499	40 412	54 752	32 486	9244
12	Fe	mg kg^{-1}, d	6678	3760	11 610	8341	1392
13	Ti	mg kg^{-1}, d	2480	2570	2738	4390	1988
14	Cr	mg kg^{-1}, d	153	452	208	77	368
15	Cu	mg kg^{-1}, d	1240	3865	689	711	268
16	Mn	mg kg^{-1}, d	105	413	236	176	55
17	Ni	mg kg^{-1}, d	48	249	104	29	12
18	Zn	mg kg^{-1}, d	563	1380	736	53	229
19	Sb	mg kg^{-1}, d	73	138	81	2.2	537
20	As	mg kg^{-1}, d	3.4	4	7.8	4.4	0.7
21	Ba	mg kg^{-1}, d	468	490	1510	360	278
22	Cd	mg kg^{-1}, d	1.1	1.1	2.2	0.2	0.7
23	Co	mg kg^{-1}, d	3.6	6	8.5	4.4	3.4
24	Pb	mg kg^{-1}, d	280	162	179	25	31
25	Mo	mg kg^{-1}, d	12.4	8	19	1.8	3.2
26	Se	mg kg^{-1}, d	1.2	1.4	2.2	3.8	0.5
27	Tl	mg kg^{-1}, d	0.5	0.5	0.5	0.4	0.5
28	Sn	mg kg^{-1}, d	26	67	41	8	12
29	V	mg kg^{-1}, d	20	11	25	54	8.0
30	Hg	mg kg^{-1}, d	0.15	0.5	0.8	0.1	0.1

lightweight waste components (rubber, plastic or textile) that might contain a high chlorine and cadmium content classified by the air classifier (due to their lighter density/weight) and put into the SRF stream. The other reason might be that some waste components containing high chlorine and cadmium content were picked up by the NIR sorting unit during its positive sorting and added into SRF stream. This issue might be related to the lack of capacity or proper maintenance checks of the NIR sorting unit (especially air nozzles) or non-steady flow rate of waste material (sometimes there could be sudden peaks of material flow from sorting units due to non-steady material feeding at the start of process) passing through the NIR sorting unit on conveyor belt. In newly built SRF production plants, NIR sorting technology is being increasingly installed, which is capable of removing highly chlorinated plastic polymers (Roos and Peters, 2007; Schirmer et al., 2005) but improvements in this sorting technology are necessary for full operational scale (Pieber et al., 2012). In the case of mercury and arsenic, higher mass flows of their respective input content were found in fine fraction stream. This might be linked with the fact that waste components in the input waste stream containing mercury and arsenic content were shredded to a smaller particle size (<15 mm) in the primary shredding and screened out as a fine fraction.

Conclusion

In this research, the elemental quality of SRF produced from MSW was examined in detail. The stream of MSW used to produce SRF was energy waste collected from households. The quality evaluation was based on the elemental analysis of waste components, the input and output streams, and the elemental balance of the SRF production process.

In the SRF production process, a higher mass flow of the input chlorine and cadmium was found in the SRF compared with the other output streams. Of the input of chlorine and cadmium to the process, 55% and 62%, respectively, was found in the SRF. In case of arsenic and mercury, of their input content to the process, higher mass was found in the fine fraction compared with the other output streams. Of the input arsenic and mercury content, 45% of each was found in fine fraction. Lead was found to be comparatively homogenously distributed among the SRF, fine fraction and reject material.

Among the components of MSW, rubber, plastic (hard) and textiles (synthetic type) were identified as the potential source of polluting elements and PTEs and their distribution in the output streams of SRF production played a decisive role in defining the elemental quality of the SRF. In particular, the sorting of rubber

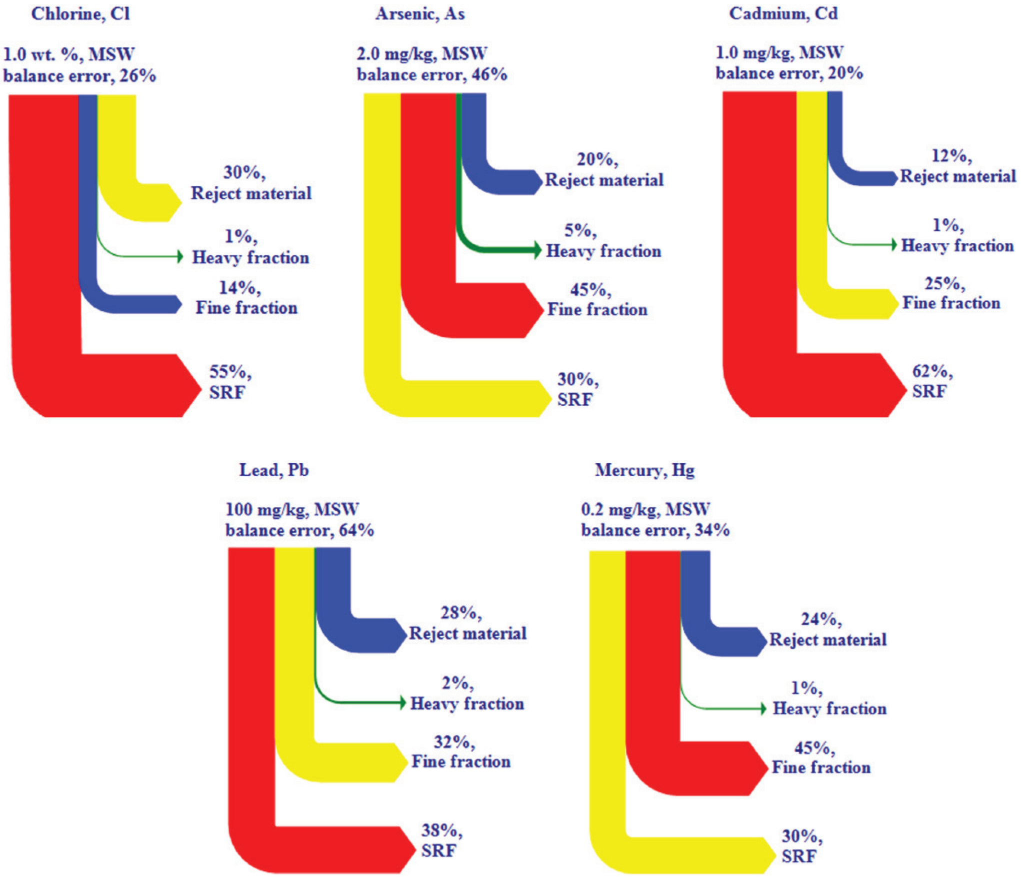

Figure 4. Elemental balance of SRF production process: SRF produced from MSW (energy waste collected from household). MSW, municipal solid waste; SRF, solid recovered fuel.

and hard plastics (PVC-plastic) from the input waste stream into the output streams was recommended to be monitored very carefully. On the other hand, paper and cardboard, wood and plastic (soft) were identified as the least containing of the polluting elements and PTEs, and their maximum recovery in the SRF stream effectively reduced the content of polluting elements and PTEs, and enhanced the yield of SRF.

Declaration of conflicting interest

The authors declare that there is no conflict of interest.

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