Biomass pre-treatment for bioenergy

Case study 3:

Pretreatment of municipal solid waste (MSW) for gasification

IEA Bioenergy

InterTask project on Fuel pretreatment of biomass residues in the supply chain for thermal conversion

Biomass pre-treatment for bioenergy

Case study 3 – Pretreatment of municipal solid waste (MSW) for gasification

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Abstract

Gasification is a flexible technology for converting solid fuels into heat, power, chemicals or fuels. When applied to biomass-based materials, carbon-neutral energy production is possible. Biomass gasification is a well-established technology, but typical biomass feedstock materials tend to be relatively expensive and the process is generally not cost-competitive. Waste materials such as municipal solid waste (MSW) include high fractions of non-recyclable but combustible biomass/ organic components such as paper, cardboard, wood, textiles and plastics that make MSW an interesting opportunity fuel for gasification systems. In addition, a gate or tipping fee is usually paid to the receiving facility by the waste disposer and that fee can favourably alter the economics of an energy production plant.

By its nature, MSW is very heterogeneous both physically and chemically, which creates operational challenges for energy conversion systems. In addition, the physical nature of waste complicates mechanical feeding into such systems. In order for MSW to be used in systems such as gasifiers, it should be pre-treated to remove non-combustible materials, homogenized to minimize operational variations, and ideally transformed to a physical nature compatible with mechanical feeding systems.

This report, prepared through collaboration between IEA Bioenergy Task 33 (Gasification of Biomass and Waste) and Task 36 (Integrating Energy Recovery into Solid Waste Management Systems), examines technical and economic aspects of MSW pretreatment, focusing on two established technologies, mechanical pretreatment and mechanical-biological pretreatment. Case studies in Germany and Italy, considered representative of many countries within IEA Bioenergy, are presented.

The evaluation highlights that mechanical and mechanical-biological pretreatment of MSW can allow waste to meet the physical and chemical specifications required of gasification facilities. The pretreatment processes are relatively straightforward and involve several stages of sorting, separating, size reduction, and in some cases, biological treatment. Capital costs for the pretreatment systems are moderate and generally worth the benefit of making a low-cost, readily available feedstock stream available. Overall economic analysis is favourable, but viability depends strongly on received gate/tipping fees associated with collecting the municipal waste.

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1 Introduction

Bioenergy technologies are an important aspect of sustainable global energy production. Since biomass represents the only renewable source of carbon, society is moving into a bio economy with closed loops for carbon and nutrients. As demand increases, it becomes more relevant to explore opportunities for diversifying the resource base to lower grades of biomass, thereby reducing logistical costs and increasing fuel flexibility of various conversion technologies.

Lower grade fuels such as municipal solid waste (MSW) may have relatively high nitrogen contents or ash fractions, low ash melting temperatures, high moisture content, excessive particle size, or contain unwanted components such as heavy metals. These undesirable properties may create operational problems in feeding the material into an industrial system or converting the feedstock to a final energy carrier (e.g. heat, electricity, gaseous or liquid biofuels). Pre-treatment through the use of additives, leaching or thermal conditioning may provide an attractive approach for enabling the use of low-grade fuels such as waste residues.

Pretreatment can be defined as all intermediate process steps, through which physical or chemical characteristics of a biomass resource are modified on purpose, before it is used for final conversion into a useful energy carrier. This includes for example sorting, separation, mechanical size reduction and biological treatment.

This report is one of five separate case study reports that illustrate the added value of pretreatment technologies in specific fuel supply chains. It relates to pretreatment of municipal solid waste (MSW) intended as (co-)feed for gasification systems. State of the art gasifiers mostly run on comparatively high quality wood at specifically high fuel cost in combined heat and power (CHP) operation. Similarly, state of the art waste incinerators (either grate firing or fluidized bed combustion) transform waste into environmentally non-hazardous products, making use of the energy content in CHP operation. Waste gasification opens up opportunities for raw material utilization of waste in the sense of a circular economy (i.e. a closed carbon cycle). In combination with biomass, waste feedstock may increase impacts on CO_2 reduction and replacement of fossil material in production of energy and chemicals. Waste is a particularly inexpensive fuel, typically bringing a gate fee (tipping fee) to the receiving facility. Compared to wood, waste has a similar calorific value and is partly renewable, but it is a very heterogeneous fuel that requires intense pretreatment.

This report presents an analysis of two pretreatment technologies for MSW to make it suitable for feed or co-feed to gasification systems: mechanical pretreatment and mechanical-biological pretreatment. Case studies for application in Germany and Italy are described, with consideration of technical and economic aspects.

2 Waste pretreatment technology descriptions

2.1 MECHANICAL PRETREATMENT

In this case study of mechanical pretreatment, municipal solid waste (MSW) is chosen from the variety of waste streams because in most IEA Bioenergy countries waste is available in large quantities as a potential gasification fuel source. Despite being inhomogeneous, it brings the advantage of not being burdened with too high heavy metal, halogen or alkaline content as other waste streams like sewage sludge, electronic waste, or industrial hazardous waste streams might be. MSW pretreatment is a non-standardized process widely applied with the purpose of pre-sorting and recycling waste fractions. The major fuel-type product derived from MSW is refuse derived fuel (RDF), which is primarily targeted towards the purpose of combustion. A standard for solid recovered fuel (SRF), which is a more strictly defined sorted waste, is under development (ISO/TC300). Waste pretreatment includes mechanical and/or biological technologies as well as manual sorting. Today, most RDF is burnt applying waste-to-energy incineration technologies.

In case higher shares of RDF (lower fraction of biomass) shall be gasified, either the gasifier type and gas cleaning technology have to be adapted to this fuel and/or increased pretreatment is necessary to match the fuel specifications required for gasification. This is especially true if other than bulky MSW shall be considered. Here, a 100MW circulating fluidized bed (CFB) gasifier type is chosen as reference to produce dust free syngas for application in a cement kiln.

In Table 1, key parameters of untreated MSW and CFB-feed are summarized according to the gasification process requirements. Note that the MSW values can give an indication only, in this case referring to the EU-27 countries. In section 2.3, limited gasification plant data is analyzed in more detail.

Table 1. Key parameters of CFB-feed according to the gasification process requirements and untreated MSW

Parameter		CFB – Feedstock[1,2]	Municipal Solid Waste (MSW) [3]
Particle size			
Maximum diameter	[mm]	50	> 300
Proximate analysis			
Moisture content	[wt-%]	≤ 35	15 - 35
Volatile matter	[wt-%]	≤ 75	
Ash content	[wt-%]	≤ 25	25 - 35
Ultimate analysis			
Sulfur	[wt-%]	< 1	0.3 – 0.5
Chlorine	[wt-%]	< 2	0.4 – 1.0
Mercury	[mg/kg]	< 1.5	0.5 - 11
Ash melting point	[°C]	≥ 960	
LHV	[MJ/kg]	~ 10 - 20	7 - 15
Bulk density	[t/m³]	0.25	0.1

In order to produce the CFB feedstock according to the parameters mentioned above, the mechanical processing procedure shown in Figure 1 is applied.

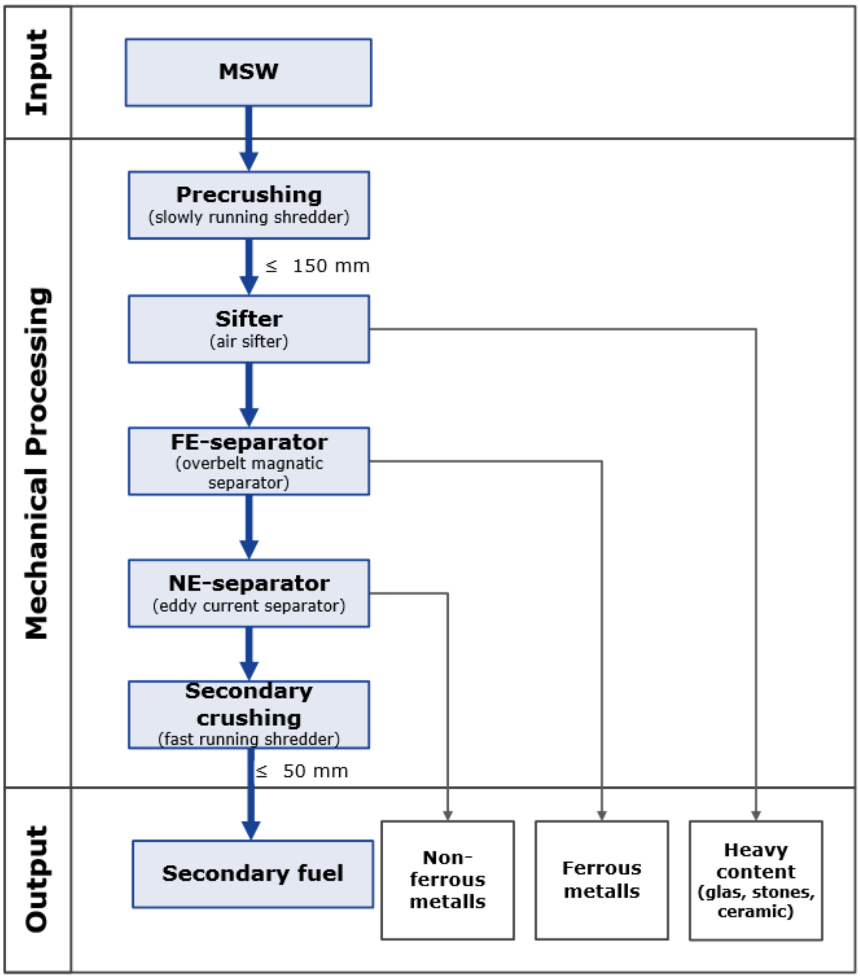

Figure 1. Description of the mechanical treatment process selected to fulfil the specifications according to Table 1.

The boundary conditions are defined as an input of 30 t/hr of MSW and an output of more than 20 t/hr of secondary fuel with a lower heating value (LHV) of ca. 10 MJ/kg.

In the first step, the MSW is precrushed using a slowly running shredder to generate a size distribution more homogeneous than the original MSW and to increase the bulk density. Afterwards, heavy contents like glass, stones and ceramics are removed using a wind sifter. This process step is of specific importance for the ash melting temperature of the feedstock. During this step, the LHV increases. In the third and fourth steps the ferrous and non-ferrous metal components are removed by an overbelt magnetic separator and an eddy current separator, respectively. Secondary crushing of the remaining fractions using a fast running shredder decreases the particle size to a value of less than 50 mm, while increasing the bulk density.

Referring to mechanical pretreatment of average MSW collected in Germany, approximately 1.2 wt-% of non-ferrous metals, 1.8 wt-% of ferrous metals, 10 wt-% of heavy content and 2.0 wt-% of water are separated, each one referring to the original composition of the MSW [4,5]. The bulk density increases from approximately 0.1 t/m³ to 0.25 t/m³. In parallel, the LHV rises to a value of

9.5 MJ/kg, starting from a value of 8.0 MJ/kg. The secondary fuel from mechanical treatment of MSW by the process described above fulfils the feedstock requirements of the mentioned CFB gasifier [6,7,8].

2.2 MECHANICAL BIOLOGICAL TREATMENT

Mechanical Biological Treatment (MBT) is a generic term that includes different mechanical processes, like grinding, shredding, dimensional sorting, etc., as well as biological processes like biostabilization, composting through aerobic digestion, and anaerobic digestion.

The MBT concept first originated in Germany in the early 1990s as a consequence of the need to find alternatives for waste treatment following regulatory restrictions on landfill and subsequent landfill bans, as well as increased cost for alternative disposal than incineration. The MBT plant technologies are established over the world and the largest European markets, which counted over 330 MBT facilities in operation in 2011 [9], include Germany, Austria, Italy, Switzerland, the Netherlands and, more recently, the UK.

Usually, MBT is a residual waste treatment process that involves both mechanical and biological treatments. To achieve the different required targets of recycling, recovery, composting or anaerobic digestion, MBT plants are configured in a variety of ways. The biological step of an MBT plant can be prior to or after mechanical sorting of the waste, as illustrated in Figure 2.

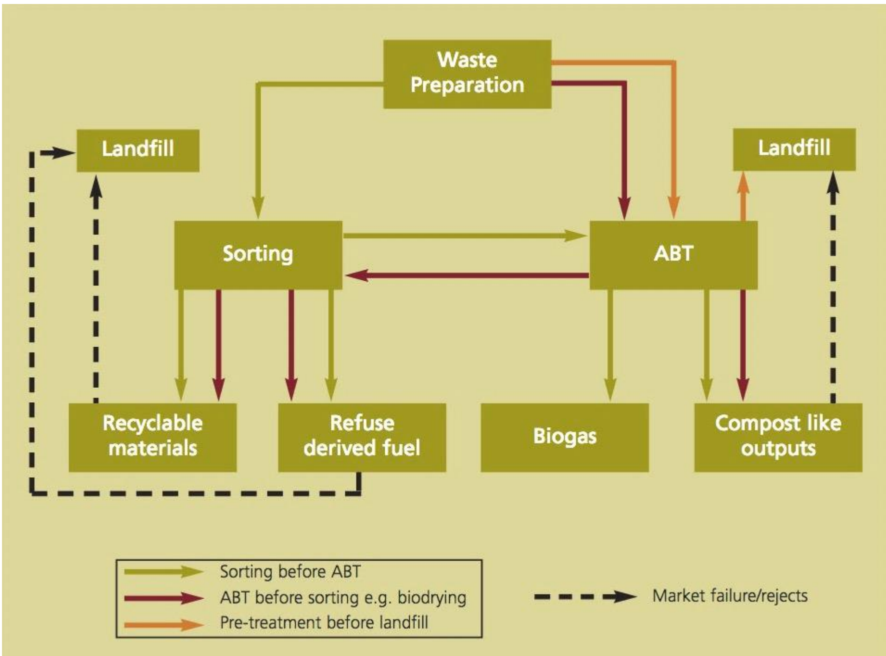

Figure 2. Different outline of an MBT plants [10].

Residual waste requires preparation before biological treatment or sorting of materials can be applied. Initially, bulky waste is removed. After this step, mechanical waste preparation techniques are applied, such as refuse bag opening and homogenization of the material by shredding into smaller particle size, to prepare the waste for the further treatment stages, like sorting or aerobic biological treatment (ABT).

The mixed waste is then sorted into different fractions including recyclable materials, refused derived fuels (RDF) and rejects to be landfilled. Depending on the plant configuration, the sorting step may precede the biological treatment, mainly when the waste contains a significant fraction of organic material.

To achieve this objectives, a number of different techniques can be used alone or in combination. A summary of the different options for waste separation is shown in Table 2 [10].

Table 2 - A summary of the different options for waste separation in MBT plants [10].

	Separation Technique	Separation Property	Materials targeted
1	Trommels and Screens	Size	Oversize – paper, plastic Small – organics, glass, fines
2	Manual Separation	Visual examination	Plastics, contaminants, oversize
3	Magnetic Separation	Magnetic Properties	Ferrous metals
4	Eddy Current Separation	Electrical Conductivity	Non ferrous metals
5	Wet Separation Technology	Differential Densities	Floats - Plastics, organics Sinks - stones, glass
6	Air Classification	Weight	Light – plastics, paper Heavy – stones, glass
7	Ballistic Separation	Density and Elasticity	Light – plastics, paper Heavy – stones, glass
8	Optical Separation	Diffraction	Specific plastic polymers

Depending on the characteristics required of the final pretreated feedstock, the key options of the biological treatment can be:

- Aerobic – Bio-drying / bio-stabilisation: partial composting of the (usually) whole waste;
- Aerobic – In-vessel composting: may be used to either bio-stabilise the waste or process a segregated organic rich fraction;
- Anaerobic Digestion: used to process a segregated organic rich fraction.

One of the outputs of an MBT plant treating MSW is material with a significant LHV that can be used in combustion or gasification processes, alone or mixed with biomass or other conventional fuels like coal.

The fuel produced through MBT is the so called refuse derived fuel (RDF), which can be defined as "a fuel produced from combustible waste that can be stored and transported, or used directly on site to produce heat and/or power".

RDF is still a waste and it is defined by the Commission Decision 2014/955/EU of December 18th 2014, amending the Decision 2000/532/EC on the list of waste pursuant to Directive 2008/98/EC. RDF is listed in this "European Waste Catalogue" (EWC) with the code and the definition: 19 12 10 "combustible waste (refuse derived fuel)".

RDF is the generic term used for this kind of fuel and should not be confused with other combustible waste, like Solid Recovered Fuel (SRF) that is a RDF that meets the classification and specifications given in EN 15359 "SRF – Specification and Classes." A suite of standards has been developed by the CEN Technical Committee 343 "Solid Recovered Fuels" and applies to fuels prepared from wastes covering terminology, classification and a number of chemical and physical characteristics, including thermal value, chlorine and mercury content.

The standardization process that aims to produce a better defined quality of RDF useful for specific purpose, including gasification and co-gasification, was recently started also at an international level (ISO/TC 300 "Solid recovered Fuels").

As an example of pretreatment of waste (mainly MSW) in MBT plants we report the situation in Italy for the year 2016 [11].

2.3 SPECIFICATION OF SRF USED IN GASIFICATION PLANTS

A limited number of references are available in the literature concerning the specification of RDF/SRF used in gasification and co-gasification plants.

We found specifications for six different SRF produced or used in Spain, Poland, Netherlands, Germany, Italy and Finland [12-19]. A summary is presented in Table 3.

Table 3. Summary of literature information

Company plant	Ecoparque de Tolrdo	GAZ-ELA Reactor	Eems-unit	Frankfurt, Lurgi CFB gasification plant	Greve, Chianti TPS CFB gasification plant	Lahti plant
Country	Spain	Poland	Netherlands	Germany	Italy	Finland
Origin	MSW	-	-	MSW + other waste	MSW + other waste	MSW + other waste
Form	Fluff	Pellets	-	-	Fluff	-
Reference and year	SFR1 2017	SFR2 2016	SFR3 2000	SFR4 1999	SFR5 1995	SFR6 2001

Table 4 reports the full set of data gathered for gasification of SRF, while Table 5 and Table 6 report statistics of the specification values for typical proprieties and for the chemical composition respectively.

Table 4. Specification values for gasification of SRF (all data)

Parameter(unit based on dry matter is not specified)	SRF1	SRF2	SRF3	SRF4	SRF5	SRF6
Particle size: (mm)	25	-	-	-	10 - 15	-
Maximum diameter (mm)	25	-	-	-	50 - 150	-
Moisture content (%) as received	-	2,5	7	15	6,5	-
Volatile matter (%)	-	86	-	-	76	-
Ash content (%)	-	18,5	16,1	21,2	11,8	6,3
Ash melting point: (°C)	-	-	-	-	1225	
LHV: (MJ/kg) as received	>25	15,4	17	16,3	17,2	16
Sulfur (%)	-	0,34	0,43	0,24	0,53	0,08
Chlorine (%)	<0,6		0,65	0,35	0,53	0,26
Ash sulfur content (%)	-	0,31	-	-	-	
Fixed carbon (%)	-	-	-	-	12,2	-
Bulk density (kg/m3) as received	-	-	-	-	600	-
Mercury (mg/MJ as received)	<0,02	-	0,04	-	-	0,02
Mercury 80° percentile (mg/MJ) as received	<0,04	-	-	-	-	-
Mercury (Hg) mg/kg	-	-	0,7	-	-	0,3
C (%)	-	49	41	42	41	-
H (%)	-	6,4	6,5	6,1	7,6	-
N (%)	-	1,1	1,5	1,2	0,28	-
O (%)	-	22	34	29	39	
As (mg/kg)	-	-	1,5	-	-	1,4
Cd (mg/kg)	-	-	2	-	-	0,1
Co (mg/kg)	-	-	1,5	-	-	
Cr (mg/kg)	-	-	70	-	-	21
Cu (mg/kg)	-	-	250	-	-	20
Ni (mg/kg)	-		25	-	-	8,5
Pb (mg/kg)	-	-	350	-	-	4,3
Zn (mg/kg)	-	-	500	-	-	74
Na (mg/kg)	-	-	-	-	-	1190
K (mg/kg)	-	-	-	-	-	670
Br (mg/kg)	-	-	-	-	-	<3
F (mg/kg)	-	-	-	-	-	43
Tl (mg/kg)	-	-	-	-	-	<0,05

Table 5. Specification values for gasification of SRF (statistics – typical proprieties)

PARAMETER	MIN	MAX	NUMBER OF DATA
Particle size: (mm)	10	25	2
Maximum diameter (mm)	25	150	2
Moisture content (%) as received	2,5	15	4
Volatile matter (%)	76	86	2
Ash content (%)	6,3	21,2	5
Ash melting point: (°C)	1225		1
LHV: (MJ/kg) as received	15,4	<25	6
Sulfur (%)	0,08	0,53	5
Chlorine (%)	0,26	0,65	5
Ash sulfur content (%)	0,31		1
Fixed carbon (%)	12,2		1
Bulk density (kg/m3) as received	600		1

Table 6. Specification values for gasification of SRF (statistics – chemical composition)

PARAMETER	MIN	MAX	NUMBER OF DATA
Mercury (mg/MJ as received)	0,02	0,04	3
Mercury (Hg) mg/kg	0,3	0,7	2
C (%)	41	49	4
H (%)	6,1	7,6	4
N (%)	0,28	1,5	4
O (%)	22	39	4
As (mg/kg)	1,4	1,5	2
Cd (mg/kg)	0,1	2	2
Co (mg/kg)	1.5		1
Cr (mg/kg)	21	70	2
Cu (mg/kg)	20	250	2
Ni (mg/kg)	8,5	25	2
Pb (mg/kg)	4,3	350	2
Zn (mg/kg)	74	500	2
Na (mg/kg)	1190		1
K (mg/kg)	670		1
Br (mg/kg)	<3		1
F (mg/kg)	43		1
Tl (mg/kg)	<0,05		1

Table 7 reports the range of values for the lower heating value (LHV), chlorine and mercury useful for a classification of the SRF according to EN 15359 "Solid Recovered Fuel – Classification and Classes" (shown in Table 8).

On the base of the available literature data, the SRF classes complying with their use in gasification and co-gasification plants, range from 1.2.1 to 3.3.3.

Table 7. Classification of SRF for gasification

PARAMETER	MIN	MAX
LHV: (MJ/kg) as received	15,4	>25
Chlorine (%)	0,26	0,65
Mercury (mg/MJ as received)	0,02	0,04

Table 8. Classification System of SRF according to EN 15359 "Solid Recovered Fuel – Classification and Classes"

Classification Property	Statistical Measure	Unit	Classes				
			1	2	3	4	5
Net calorific value (NCV)	Mean	MJ/kg/(ar)	≥ 25	≥20	≥15	≥10	≥ 3
Classification Property	**Statistical Measure**	**Unit**	**Classes**				
			1	2	3	4	5
Chlorine (Cl)	Mean	% (d)	≤0,2	≤0,6	≤1,0	≤1,5	≤3
Classification Property	**Statistical Measure**	**Unit**	**Classes**				
			1	2	3	4	5
Mercury (Hg)	Median	mg/MJ (ar)	≤0,02	≤0,03	≤0,08	≤0,15	≤0,50
	80^{th} percentile	mg/MJ (ar)	≤0,04	≤0,06	≤0,16	≤0,30	≤1,00

3 Feedstock Availability / Resource Potential

3.1 RDF PRODUCTION IN GERMANY

In Germany, specially collected MSW is used for the production of RDF. RDF so far is a non-standardized fuel and can vary widely in composition and characteristics. An overview about the RDF specifications according to RAL-GZ 7249 is given in the VDI 3460 directive [20].

Table 9 gives an overview of the amount of waste generated in Germany in 2015 and its recovery and disposal [21].

Table 9. Waste balance in Germany in 2015.

Type of waste	Total amount of waste generated	*Of which:* waste deposited in waste treatment plants with					Recovery rate
		disposal operations			recovery operations		
		landfilling	thermal disposal	treatment for disposal	energy recovery	recycling	
	1,000 tons						%
Total	**402,229**	**71,570**	**8,356**	**4,571**	**43,113**	**274,619**	**79**
Of which:							
Municipal wastes	51,625	104	3,917	1,084	12,068	34,453	90
Wastes resulting from mining and treatment of mineral resources	31,426	30,789	1	28	5	603	2
Construction and demolition wastes	208,997	22,725	126	985	1,459	183,702	89
Secondary wastes	50,964	4,877	1,271	811	15,671	28,333	86
Remaining wastes (in particular of manufacturing and other economic activities)	59,218	13,075	3,042	1,663	13,911	27,527	70

The recovery rate refers to the waste input to all recovery operations, this includes recycling, as well as energy recovery, where the waste is used to substitute conventional energy sources to generate electricity and heat. The amount of waste used in energy recovery processes is about 11% relative to the total amount of waste, whereas relative to the municipal and industrial waste, the percentage increases to 23%.

In Figure 3, the development of the treatment of municipal waste by incineration, mechanical (biological) treatment M(B)T and mechanical-biological/mechanical-physical stabilization (MBS/MPS) and the usage in RDF power plants in Germany is shown [22]. The abbreviation "AbfAblV" means Abfallablagerungsverordnung, which is German regulatory about the disposal of waste equivalent to the execution of a landfill ban for MSW.

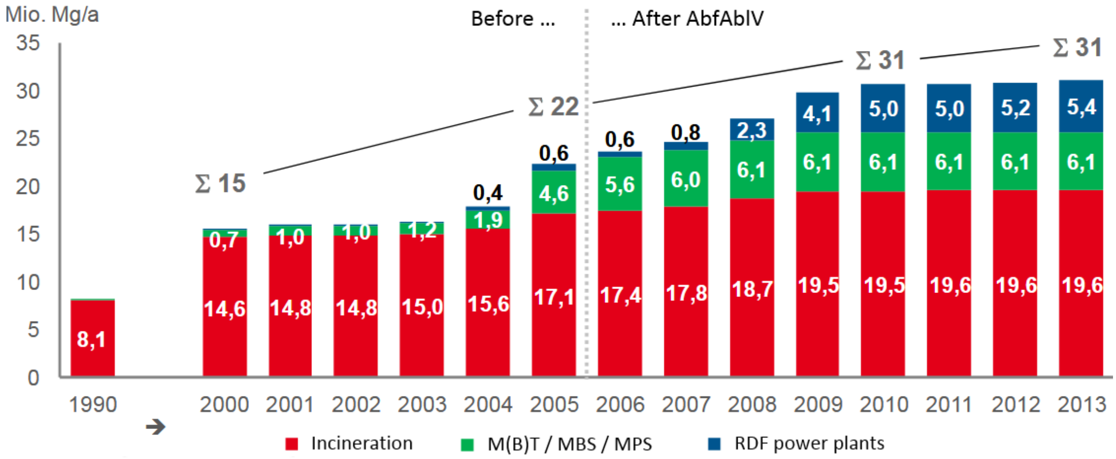

Figure 3. Development of the municipal waste treatment in Germany [32].

In 2013, 68 incineration plants, 61 M(B)T/MBS/MPS plants and 35 RDF power plants were in operation in Germany. Together, all plants treated 31 million tons per year of MSW. This value has remained stable since 2010, and doubled since 2000 due to the landfill ban for MSW. Capacity utilization of Germany's MSW treatment facilities is constantly close to name plate capacity.

Currently, roughly 25 mechanical treatment plants are operated in Germany [23]. Together they treat ca. 2.6 million tons per year of MSW. For all of the M(B)T/MBS/MPS/MT plants the average output of secondary fuel is about 60%, and without MT around 50%. Thus, annual German RDF production amounts to ca. 3.5 million tons. Today, most RDF from these plants is burnt either in RDF power plants or in cement kilns, mostly in co-combustion with other conventional fuels.

3.2 RDF/SRF PRODUCTION IN ITALY

As an example of pretreatment of waste (mainly MSW) in MBT plants we report the situation in Italy for the year 2016 [24].

The amount of MSW production in Italy was 30.1 million tons in 2016. Unsorted MSW production, after separated collection, was 14.3 million tons. 69% of this (9.8 Mton) was treated in MTB plants, together with 1.2 Mton of other waste, for a total of 11 million tons of waste. The gross capacity of the Italian MBT plants is around 17 Mton. Figure 4 reports this data in terms of percentage.

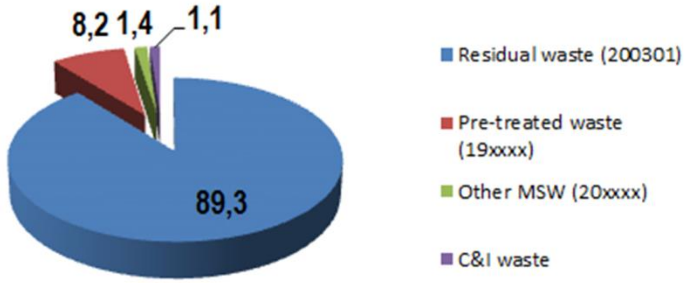

Figure 4. MSW management in MBT plants in Italy in 2016 [24].

Figure 5 shows the mass balance of the output of the treatment process, that results in the production of eight main fractions (dry fraction, biostabilized fraction, SRF, organic fraction, biodried fraction, rejects and percolates, recovered materials and uncosposted organic fraction). The figure also indicates the final destination of each of the eight sorted fractions.

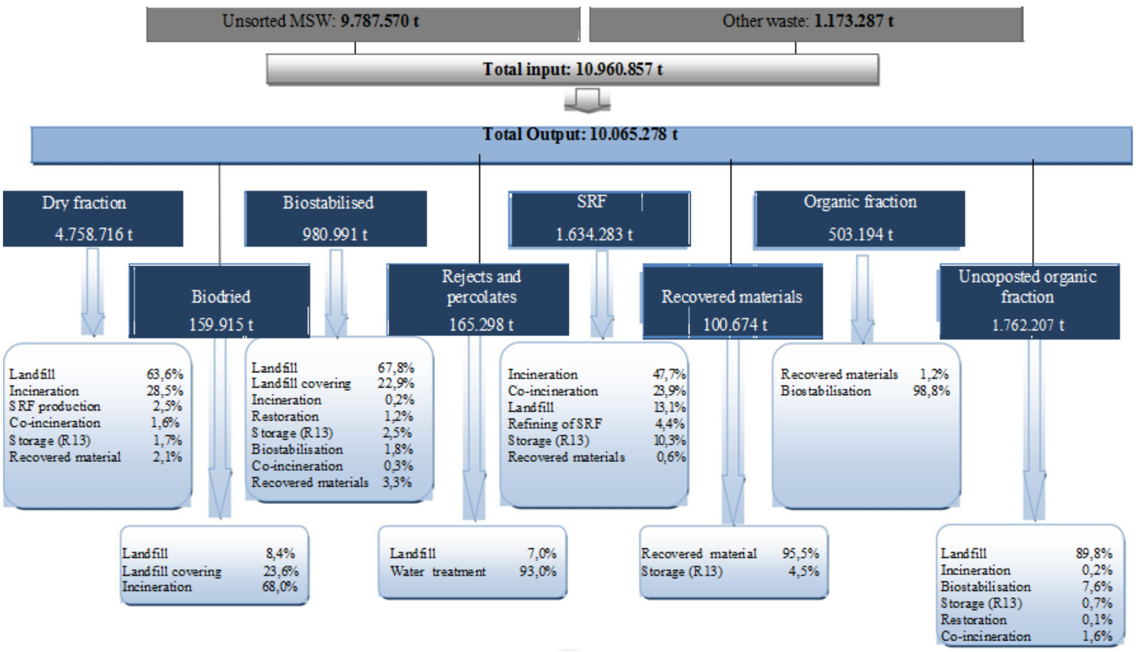

Figure 5. MTB plants in Italy: mass balance and output destination in 2016

Figure 6 shows the same data ranked based on fraction and final destination. In this example one should take into account that in Italy the terms RDF and SRF are synonymous, as all the RDF must meet the EN 15359 requirements. This explains why the output in SRF is 16.2% of the input MSW, while the amount sent to incineration and co-incineration is the 27.4%, the latter including other combustible waste not meeting the EN 15359.

If we assume that all the SRF produced can be also used in gasification and co-gasification plants, being the higher quality of the total combustible waste produced, the potential would be 1.78 million tons per year.

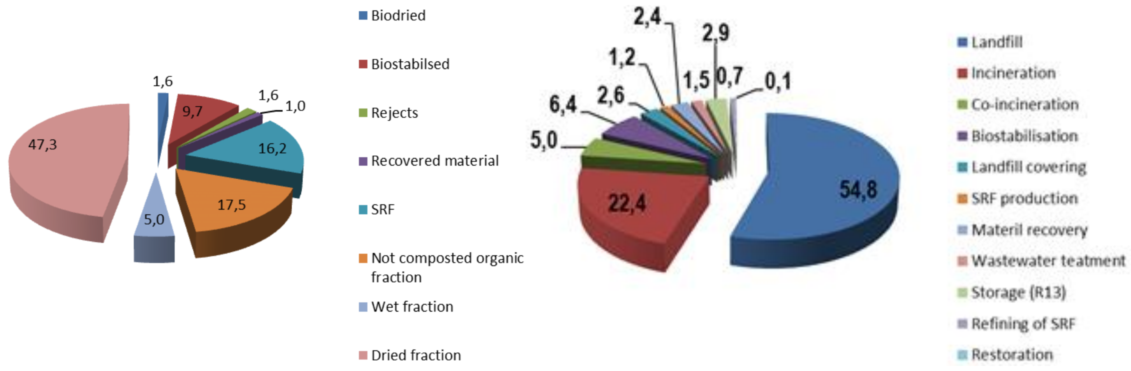

Figure 6. MTB plants % output (left) and destination (right) in Italy in 2016.

4 Economic Considerations

4.1 RDF IN GERMANY

The cement plant at Rüdersdorf, Germany, operates a CFB gasifier with a thermal capacity of 100 MW to supply syngas made of various secondary fuels to the calciner of the plant. The CFB-gasifier was commissioned in 1996 and since then has undergone feedstock extensions and optimizations [25-27]. The range of secondary fuels used in the CFB-gasifier is wide: the LHV can vary between 1 -35 MJ/kg; the water content should be below 50% [28,29]. Certain feedstock requirements have to be fulfilled, since the CFB-technology in combination with the upstream cement process put limits on feedstock content of metals, PVC or glass.

For this study, this gasification case is taken as a pretreatment reference assuming that two-thirds of the gasifier thermal load have to be provided by MSW-to-RDF pretreatment. The plant shall process 30 t/h of MSW receiving ca. 25 t/h of RDF of minimum quality. To calculate the costs for this secondary fuel, the costs of the construction and operation of a waste treatment plant had to be estimated in a first step (see Table 10).

Table 10. Capital investment and electricity cost of the mechanical treatment plant.

Treatment step	Manufacturer; Model	Price [€]	Electrical Power [kW]
Precrushing	WEIMA; PreCut 3000	400,000	350
Sifter	Sutco; 2-Wege-Windsichter	250,000	23.1
FM-separator	IFE Aufbereitungstechnik; -	100,000	5
NF-separator	IFE Aufbereitungstechnik; -	100,000	10
Secondary crushing	WEIMA; FineCut 2500 (2x)	640,000	2 x 250

Component price estimates were requested from the manufacturer themselves (personal communication by the author). The values of the electrical power were taken from brochures [30-33]. A plant factor of "4" was chosen to calculate the total pretreatment plant capital investment costs from the sum of component prices, assuming a brownfield installation on an existing MSW collection site. The further assumptions to calculate the MSW-to-RDF pretreatment price are listed in Table 11.

Table 11. Estimated values needed to calculate the price of secondary fuel generated by mechanical waste treatment.

	Parameter	Value
Operation of plant	Operating hours	8,000 hr/a
	Electricity	0.1 €/kWh
Annual costs	Depreciation Period	10 years
	Depreciation rate	10 % of invest/a
	Capital costs	10 % of invest/a
	operating costs	5 % of invest/a
Revenues & Fees	Revenue: Ferrous Metals	25 €/t
	Revenue: Non-Ferrous Metals	250 €/t
	Landfill Fees: Heavy Content	30 €/t

This results in the following cost estimates:

- The sum of investment to build the mechanical treatment plant is 5,960,000 €, therefore the annual fixed costs are 1,490,000 €.
- The annual costs for electricity are 710,480 €.
- 4,320 tons of ferrous metals and 2,880 tons of non-ferrous metals can be sold per year, which results in an annual income of 828,000 € under the assumption of total metal separation.
- The separated heavy contents have to be disposed; the landfill fees lead to annual costs of 720,000 €.

Summarizing, the mechanical treatment to produce 204,000 tons per year of secondary fuel incur an annual cost of 2,092,480 €. This gives the treatment costs of **10.30 €/t** of secondary fuel.

To consider the uncertainty of the data and calculations mentioned above, a sensitivity analysis was conducted. The data is listed in Table 12.

Table 12. Parameter varied and variation range for the sensitivity analysis.

Parameter	Basic costs	Variation Range of sensitivity analysis
Annual Costs: Treatment Plant	25 % of Invest	+/- 25 %
Electricity	0.1 €/kWh	+/- 50 %
Revenue: Ferrous Metals	25 €/t	+/- 20 %
Revenue: Non-Ferrous Metals	250 €/t	+/- 20 %
Landfill Fees: Heavy Content	30 €/t	+/- 25 %

This leads to a range of the treatment costs from 5.00 – 15.52 €/t of secondary fuel, which is a variation of +/- 51 % around the price calculated before.

The current waste incineration gate fee for MSW in Germany is on the order of 100 €/t. Due to high capacity utilization of all treatment plants holding a waste treatment permit in combination with a constant amount of MSW as well as other waste types, no significant MSW gate fee decrease is to be expected. Thus, taking into account transportation cost of RDF secondary fuel from MSW-to-RDF mechanical pretreatment, RDF can bring a significant feedstock cost advantage in co-gasification compared to all kind of non-fossil as well as biomass based fuels.

4.2 RDF/SRF IN ITALY

Computing the cost of waste pretreatment in MBT plants for RDF/SRF production, there are a wide range of individual costs to be considered, depending upon the complexity of the technology, the adopted biological process, and the technological level of the particular MBT plant.

The main income for a MBT plant is the gate fee that is in competition with other option like direct landfilling or incineration of the residual waste.

In the UK, the average received gate fee income from wastes into MBT processes was 79 £/ton in November 2011/February 2012, with variances from 65 £/ton to 84 £/ton. This compared to 84 £/ton in the 2011 , 75£/ton in 2010 and 62 £/ton in 2009 [34].

In Italy (2014 data) the average received gate fee income is 112,.3 €/ton, with significant differences between regions, from 87.6 €/ton in Lazio to 142.6 €/ton in Piemonte. These data do not consider the gate fee for Liguria (210 €/ton) and Sicilia (28,4 €/ton), because these values are considered unrepresentative due to particular logistical reasons [35].

The pretreatment costs are sensitive to the market value of the recycled materials, produced RDF and soil conditioners, as well as the gate fee and taxation level for transport and landfilling of residual waste and for the incineration of the lower quality of the produced RDF.

Other costs to be considered include electricity, for which the cost is significantly different if the MBT plant includes an electricity production facility, the costs for water and chemicals to reduce the diffused emission (e.g. odour and dust), and the cost of treatment of the wastewater and leachate.

Furthermore, there are investment, maintenance, labour and insurance costs. Capital costs for MBT facilities are relatively high. Recent estimations for the construction of MBT plants fall in the range of 50–125 M£ for MBT facilities in the capacity range 80 – 225 kton/year [36].

Specific costs of MBT plants in Italy

We considered specific costs of four MBT plants located in northern Italy, that are potentially able to produce SRF complying with the range of classes (1.2.1 – 3.3.3.) identified in the our literature survey (ref Table 8).

The first three plants are based on a single flow technology with a single biodried stage carried out on the whole incoming waste. The outgoing SRF is transferred to cement kilns, to fluidized bed incineration plants and to grid incineration plants, or completely to a fluidized bed incineration plant, respectively (Figure 7).

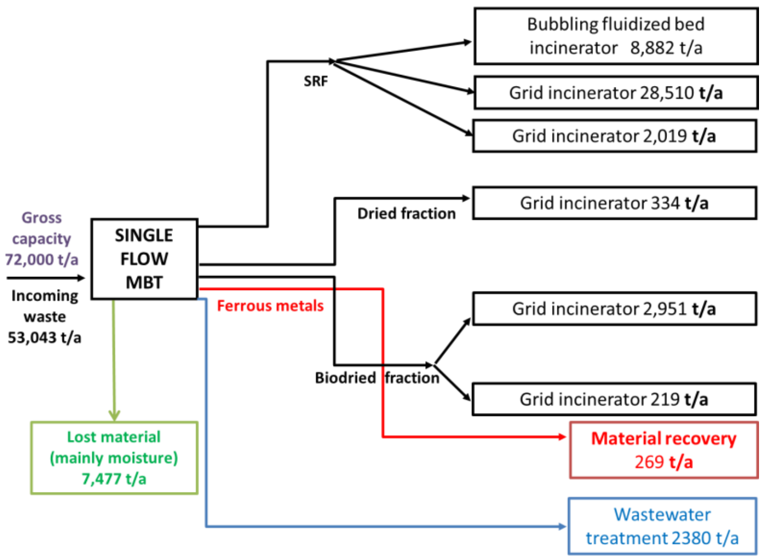

Figure 7. Example of a single flow technology MBT with a single biodriying stage and final destination of the produced SRF to a fluidized bed plant and to a grid incineration (2015 data).

The fourth MBT plant is based on a separated flow technology where the incoming waste is at first mechanically separated in two fractions, namely the dry fraction (comparable to the residual unsorted MSW), and a wet fraction (organic fraction). The organic fraction is then submitted to a biodrying stage. The outgoing SRF is transferred to a fluidized bed incineration plant (Figure 8).

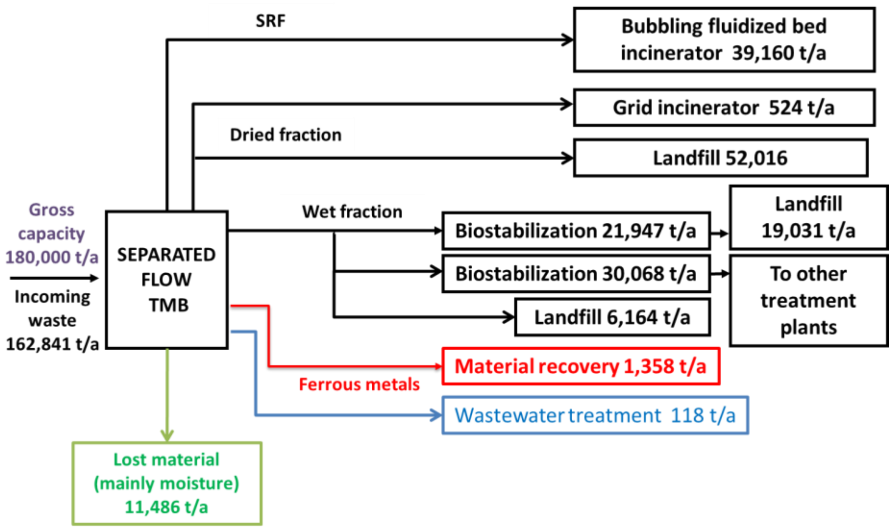

Figure 8. Example of a separated flow technology MBT with a biodried stage carried out on the separated organic fraction and final destination of the produced SRF to a fluidized bed plant (2015 data).

The overall performance of the four considered MBTs is reported in Table 13.

Table 13. Performance of the four considered MBTs.

MBT Plant	1	2	3	4
Total waste treated (t/a)	66.537	131.309	53.043	162.841
SRF produced (t/a)	22.924	60.997	39.412	39.160
LCV of the SRF (MJ/kg)s	18-20	> 13	13,4 - 16,6	15

Table 14 shows the range of specific costs for the four considered MBTs. Figures refer to the declared costs from the owner of the plant. When not specified costs include the actual transport cost.

Table 14. Specific costs for the four considered MBTs.

MBT Plant	Average	Min	Max
Total waste treated (t/a)	119.5	97.3	142.6
SRF produced (t/a)	20	10	30
LCV of the SRF (MJ/kg)s	125	100	150
Income (€/ton)			
Gate fee for incoming waste	111	83	153
Ferrous metals recovered	20	0	40
Non ferrous metals recovered	11	0	20
Outcome (€/ton if not indicated)			
Landfilling	111	83	153
SRF (highest quality)	20	0	40
SRF transport costs	11	0	20
Other combustible residues	95	90	100
Wastewater treatment	49	25	70
Electricity (€/kWh)	-	0.05	0.16
Diesel oil	1200	-	-
Labour costs	9.8	6.1	20.2
Maintenance costs	10.4	8.2	14.8
Mortgage	4	-	-
Insurance costs	0.07	-	-
Treatment cost (€/ton)	**80**	**52**	**118**

The difference in the gate fee for incoming waste is due to the cost applied in different regions.

The cost for landfilling depends both on the particular regional cost, which include a different local landfilling tax (10.3 €/ton in Lombardia, 18.1€/ton in Piemonte and 25.17 €/ton in Emilia Romagna) and on the availability of a landfilling located in the same site where MBT plants are operated.

Only the highest quality of the produced SRF was considered. In Italy, as already mentioned, all the RDF should comply with EN 15359 "SRF – Specification and classes." RDF not matching this standard or belonging to a SRF class defined by the EN 15359 for which the specific plant is not authorized, are reported in Table 9 as "other combustible residues" and are usually classified with the EWC number 19.12.12. For this kind of material a higher gate fee is usually applicable both for the use in co-combustion and incineration, and would likely also apply for gasification applications.

The cost of the electricity ranges from 0,05 €/kwh when self-produced in the same location where the MBT is operating, to 0.16 €/kwh (standard cost for buying).

Labour, maintenance, mortgage and insurance costs have been normalized per ton of incoming waste. Positive costs include only the gate fee for income waste, and the revenue for selling the recovered ferrous and non-ferrous metals, but from an economic point of view the gate fee is the only significant income.

On the base of the specific costs listed in Table 9, the treatment cost for the four considered MBTs have been calculated. The treatment cost follows in the range of 52 - 118 €/ton with an average value of 80 €/ton of income waste.

As an example, Table 15 shows the economic balance for the plant number 4 of Table 13, for which the more completed set of specific costs was provided by the owner. A gross revenue of 28% of the total operating costs seems to be a good figure, but one should take into account that the provided specific costs refers to one year only (2015) and could not include costs for extraordinary repairs and/or replacement of some vital components, as well as costs for the end of life management of the plant.

Table 15. Economic balance for the plant number 4 of Table 13.

Income (€/a)	**Min**	**Max**
Gate fee for income waste	19.329.227	19.329.227
Ferrous metals recovered	6.790	6.790
Nonferrous metals recovered	0	0
Total	**19.336.017**	**19.336.017**

Outcome (€/a)	**Min**	**Max**
Landfilling	7.594.218	7.594.218
SRF	1.574.232	1.574.232
SRF transport costs	0	0
Wastewater treatment	8.210	8.210
Electricity	794.427	794.427
Diesel oil	0	0
Labor costs	859.000	859.000
Maintenance and extra costs	2.402.586	2.402.586
Mortgage	663.646	663.646
Insurance costs	11.000	11.000
Total	**13.907.320**	**13.907.320**

Income minus outcome (€/a)	**5.428.697**	**5.428.697**
Gross revenue (%)	**28**	**28**

5 Conclusions

Mechanical pretreatment

In a bottom-up approach, mechanical pretreatment of MSW has been evaluated according to a case study in Germany for the requirements of a large scale CFB gasifier producing syngas with low level quality requirements for energetic utilization. Considering the current market situation in Germany, pretreatment costs sum up to 10 – 15 € per ton of RDF (>80wt% of incoming MSW is recovered as RDF) with an average income value of approximately 100 €/t of MSW. This indicates the upper-limit potential of RDF for co-gasification. German annual RDF production achieves ca. 3.5 million tons.

Mechanical biological pretreatment

Gasification plant requirements in terms of feeding fuel characteristics, and literature data can give us produce a picture of the specification for RDF/SRF produced in MBT plants, that are or can be used in gasification and co-gasification plants.

According to EN 15359 "Solid Recovered Fuel – Classification and Classes" the already used SRF for this purpose belongs to the class falling in the range 1.2.1 to 3.3.3.

On this basis there is significant potential for producing RDF to be used in gasification and co-gasification plants both in Europe and over the world.

In computing the cost of waste pretreatment in MBT plants for RDF/SRF production, there is a wide range of individual costs to be considered, depending upon the complexity of the technology, the adopted biological process, and the technological level of the particular MBT plant.

The pretreatment costs are sensitive to the markets value of the recycled materials, produced RDF and soil conditioners, as well as the gate fee and taxation level for transport and landfilling of residual waste and for the incineration of the lower quality of the produced RDF. Other costs to be considered include electricity, for which the costs will be significantly different if the MBT plant includes an electricity production facility, the costs for water and chemicals to reduce the diffused emission (e.g. odour and dust), and the cost of treatment of the wastewater and leachate. Furthermore there are investment, maintenance, labour and insurance costs.

Analysis of specific pretreatment costs for four selected MBT plants operating in the north of Italy indicated that positive costs (those giving a net income) include only the gate fee for incoming waste and the revenue for selling the recovered ferrous and non-ferrous metals, but from an economic point of view the gate fee is the only significant income.

The major negative costs (those giving a net outcome) include landfilling and/or incineration of low LHV residues, maintenance and operations, followed by electricity, labour and mortgage of the capital investment.

The resulting pretreatment cost range from 52 to 118 €/ton with an average value of 80 €/ton of incoming waste.

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