Technical-economic evaluation of an advanced MBT process to enrich biomass as renewable fuel

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Abstract

In order to fulfil the EU-Landfill Directive by reducing the amount of biodegradable waste being landfilled the EU-Life+ demonstration project MARSS (Material Advanced Recovery Sustainable Systems) was designed. To enhance the efficiency of mechanic biological treatment plants (MBT), the primary objective of MARSS is to demonstrate that there is an effective way to post-treat dried/stabilized mixed municipal solid waste (MMSW) from the MBT output. Consequently a refined renewable biomass fuel (RRBF), suitable for the combustion in small and decentralized combined heat and power plants, is/can be generated. Thereby, greenhouse gas emissions will be reduced by substituting fossil fuel as well as by avoiding biodegradable substances from being landfilled. A demonstration plant was added to an existing MBT plant in Mertesdorf, Germany, where waste is aerobically dried in rotting boxes leading to a loss of water (and organic matter) of ~35 wt.-%. The dried waste has a higher net calorific value than before and is suitable to be post-treated in the MARSS plant using different sieving and separation processes. The objective is to increase the biogenic content inside the fuel with a high calorific value while separating out fossil and inert materials. These objectives were achieved by recovering approx. 42 wt.-% of the input as RRBF with a net calorific value of approx. 11,000 kJ/kg, an ash content of approx. 27 wt.-% and a fossil content of approx. 6-9 wt.-%. From an economic perspective, a post-treatment with a MARSS-module may be worthwhile if the landfilling costs are higher than 45-60 €.

1 INTRODUCTION

The treatment of mixed municipal solid waste (MMSW) prior to landfill disposal is an important measure to save resources and to prevent or reduce negative effects on the environment from landfilling. Consequently, the treatment of MMSW is a commandment fixed in the European Waste Framework Directive (WFD) [1]. The WFD defines a five step waste hierarchy which, amongst others, emphasises the significance of an effective waste treatment/recycling of MMSW, in which landfilling is rated as the worst option. This is justified due to the recyclable parts of MMSW (e. g. plastics and metals) which would be lost when landfilled and thus could not be further used as raw materials in an energetic or mechanical way. Furthermore, the largest share of the MMSW are biological materials as food waste, paper, wood etc. [2, 3]. When landfilled, the biogenic waste, particularly the fast biodegradable waste components, like food waste or paper, causes greenhouse gas (GHG) emissions, which mainly consist of methane and CO_2 (each ~50 vol.-% [4]). Methane emerges through anaerobic conditions in the landfill. Its greenhouse potential is 25 times higher than that of CO_2 [5]. Because of this, Article 5,2 c of the EU Landfill Directive (LFD) demands the reduction of biodegradable waste being landfilled by at least 65 wt.-% in comparison to 1995 [6]. There are three essential waste management concepts to maintain the exigencies set by the LFD:

1. Separate collection
2. Incineration
3. Biological treatment

The separate collection gathers pre-sorted household waste and guides it into different recovery routes (e.g. glass, plastics, paper, cardboards or biogenic waste). Which parts of waste are collected separately depends on the respective EU member state and often its federal and regional legislation. Several European states are not collecting their biological waste separately which therefore ends up in MMSW [7]. However, even with a separate collection system the largest part of the MMSW is mostly biogenic material [3]. Thus, the requirements set by the LFD cannot solely be fulfilled by separate collection, but an additional treatment of the MMSW is required to reduce the high content of biogenic material.

With incineration of MMSW the requirements mentioned above can be fulfilled. However, besides biological waste, synthetic/fossil materials are incinerated as well and lead to the production of non-renewable CO_2 and other harmful emissions. Because of this, incineration plants face opposition by local stakeholders (population, politicians etc.) in many EU member states [8–10]. Modern incineration plants are designed for high throughputs of about 150,000 Mg/a [11] to decrease specific investment and treatment costs [12]. However, these large-scale plants are not economically viable in small rural areas with a slight waste volumes and long delivery routes.

As an alternative, many countries are more and more relying on the mechanical-biological treatment (MBT) technology. Numbers and importance of MBT plants strongly increased in the last decades particularly in Western, Southern and Eastern Europe [13–18]. In 2011 about 330 MBT plants were in operation in Europe, processing about 33 million Mg/a, which is expected to increase up to 46 million Mg/a and 440 plants within the next decade [19, 20]. The initial objective of the first MBT plants of the 1990s was to reduce the amount of biodegradable substances prior to landfill disposal. Thus, the long term pollution potentials (gas, leachate) of the landfill could be decreased [21, 22]. As the name suggests, MBT plants generally integrate mechanical processing with a bioconversion step. Today, numerous variations of MBT technology are under operation in the different EU countries, following individual demands by legislation and objectives arising from the specific environmental conditions. For example, the complexity of mechanical pre-treatment already varies in a MBT. Besides the primary goal of waste homogenization and shredding, specific fractions such as metal and plastic concentrates for recycling and high calorific materials for the production of refined derived fuels (RDF) are often enriched. Moreover, the goals and techniques of the biological treatment vary and can be divided into the following three concepts:

1. Aerobic degradation (known as composting) with the aim to reduce the share of biodegradable substances and thus produce a stabilized landfill material.
2. Biological drying to produce a material for energy recovery and/or further material for recycling (metals and plastics).
3. Anaerobic digestion (fermentation) for biogas production in addition with aerobic stabilization for final disposal of the residuals [23].

Many studies have been carried out to assess the environmental performance of the different MBT technologies, especially versus waste incineration, but due to the differences regarding the objective, the technology and the complexity, individual MBT systems are difficult to compare and rate to other ones [13–17, 24–27]. However, it is still certain that all biological residues of MBTs contain great amounts of biological material, at least difficult degradable materials as wood, which is still landfilled. This leads to remaining waste mass flows that still are landfilled. For instance, in 2012, 34 % of the treated waste in the EU28 was being landfilled. Ten member states even landfilled more than 70 % of their treated waste [28].

Hence, to reduce the amount of MMSW being landfilled and to comply with the LFD the EU-Life+ Project MARSS (Material Advanced Recovery Sustainable Systems, (www.marss.rwth-aachen.de) was developed. The goal of the MARSS project is to demonstrate an effective way to post-treat dried/stabilized MMSW from MBT and thus generate a refuse recovered biomass fuel (RRBF) suitable for small combined heat and power (CHP) plants. Thereby, greenhouse gas emissions will be reduced by substituting fossil fuel as well as by avoiding biodegradable substances from being landfilled. In the MARSS project a demonstration plant with a throughput of about 10 Mg/h was added to an existing MBT plant in Mertesdorf, Germany. The MBT is based on the Herhof® process, according to which the waste is dried aerobically in rotting boxes for 10 +/-1 days. Via bypass the dried/stabilized waste is fed to the new demonstration plant. There the waste is processed to RRBF using different sieving and separation processes (e. g. drum screens, flip-flow screens and air sifters). In this paper, the MARSS process will be presented in detail with regards to the main products and process requirements. On the basis of different test and measurement results, which were obtained during the one and a half year long demonstration phase of the plant, the most important boundary systems, parameter settings and findings of the demonstration phase are presented. Besides technological evaluation, the MARSS process is also analysed in terms to its economic efficiency. The information obtained from the MARSS demonstration plant was used to create a model of an industrial size plant with a throughput of 65,000 Mg/a, respectively 20 Mg/h. This model was used to determine the specific process costs of the MARSS process in industrial scale. In summary, it was possible to evaluate the economics of the MARSS process with regard of the different circumstances (landfill fee and taxes) in the EU-states.

2 MATERIAL AND METHODS

2.1 Input material characterisation

MMSW consists of different waste components which are distributed heterogeneously and vary from region to region. Influences on the waste composition are, for example, the waste management concept as well as the structural characteristics of the region in which the waste is collected. If there is a separate collection system, as for glass, paper and bio waste, less of these components will end up in the MMSW. Furthermore, differences in waste separation behaviour can be identified depending on the population structure of the region. The MMSW, which is processed in the MARSS project, comes from the region “Vulkaneifel”, Rhine Palatinate in Germany. The catchment area encompasses about half a million people of which about three quarters live in rural areas (~100 cap/km²). The other quarter lives in an area of town character (Trier) (~900 cap/km²) [26, 29]. Besides the MMSW collection, the catchment area of the MARSS project is covered by a separate collection of yard waste, glass, paper and packing waste. Unlike the majority of the Federal Republic of Germany, only 10 %[1] of this catchment area is also connected to a separate bio-waste collection system, so a large amount of biological waste ends up in the MMSW. Since the MARSS processing concept is addressed to European countries and regions which are not connected to a separate collection of bio-waste, the MMSW of the catchment area is well suited for MARSS.

Especially biogenic and sanitary materials are often wet. This leads to high water contents (up to 40 wt.-%) in MMSW. Because of material clumping, especially in the fine-grain range, effective technical processing to a biomass fuel is barely possible. Moreover, waste with a high water content possesses a low net calorific value. These reasons make it necessary to dry the MMSW before processing it to RRBF. Therefore, the demonstration plant of the MARSS project is connected to a biological drying plant. The drying boxes operate aerobically according to the Herhof Dry Stabilate® technology, drying the waste for 10 +/- 1 days. Due to the biological activity of the material, heat is produced inside the drying boxes, whereby a large part of the water evaporates over time. The average temperature of 50 °C during the drying process is controlled by the addition of fresh and recirculated (up to 70 %) air. The evaporated water is deducted with the exhaust air, condensed and biologically/chemically cleaned. Subsequently, the exhaust air is recirculated or burned via regenerative thermal oxidation (RTO). [26] By drying, a mass reduction of approximately 32-35 wt.-% is achieved on an annual average, combining a loss of water of ~27-30 wt.-% and a loss of organic matter of ~5 wt.-% [30]. The water content after drying is 15-20 wt.-%. The MMSW components can be divided into different material fractions (e. g. wood, plastics, paper, glass etc.) and/or fuel fractions. The materials used in the MARSS project were summarized into four significant fuel fractions: biogenic, fossil, inert and mixed (consisting of biogenic and fossil material, e.g. textiles). Fig. 1 shows exemplarily compositions of the dried waste (MBT output = input MARSS) of three project fuel test campaigns.

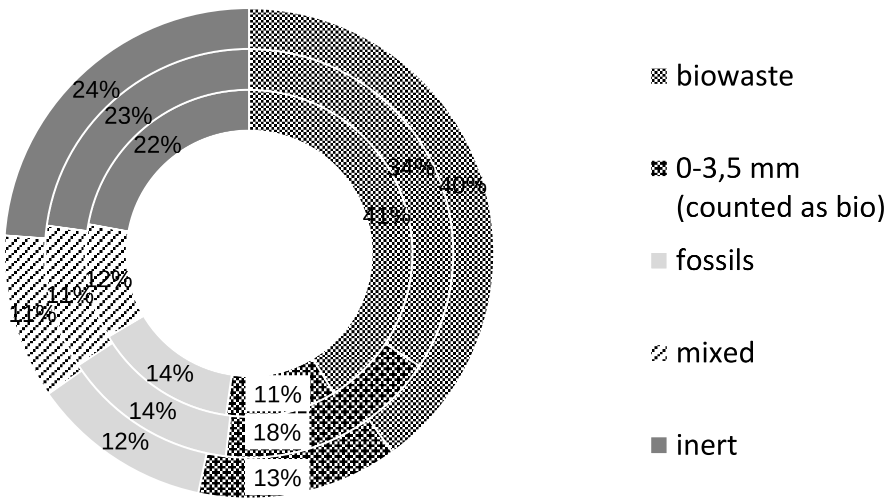


Fig. 1 Composition of the dried MMSW of three different fuel campaigns

The fraction with the highest proportion in the MMSW is the biogenic fraction with approx. 51 wt.-%. The mixed fraction, containing the material group “nappies”, residuals and textiles amount to approx. 12 wt.-%. Plastics are counted among the fossil fraction with approx. 14 wt.-%. Inert materials such as stones, ceramics, metals and glass measure approx. 23 wt.-%.

[1] 10 wt.-% of the MMSW comes from an area with a separate collection system

2.2 Issues and objectives

When processing RRBF, the biomass has to be enriched while the other fractions are sorted out. The technical feasibility and efficiency of such a processing was shown based on a demonstration plant and evaluated following five main product and process requirements (R):

R 1. Reaching a high net calorific value (~11.000 kJ/kg)
R 2. Reduction of the inert/ash content (that reduce the calorific value of the fuel)
R 3. Reduction of the fossil/ mixed fossil material content (that cannot be counted as renewable due to its fossil origin)
R 4. Recover more than 65 wt.-% of biogenic materials
R 5. Reaching a high RRBF mass recovery (more than 40 wt.-%) while reducing the amount of residuals being landfilled

In addition to a technical evaluation of the plant, an economic evaluation should be performed as well. For this reason, the MARSS project was divided into two stages:

1. The first stage included the planning, construction and testing of the MARSS demonstration plant. The planning and construction were carried out from October 2012 to August 2014. Since August 2014, the demonstration plant was in operation until the end of 2015. During this period of 1.5 years the plant was tested and optimized under real circumstances. The plant was operated in batch mode by separating different fractions on a single air sifter. During plant operation data were collected with focus on process and machine settings regarding product analyses and mass balances. The main findings of the demonstration phase are presented in this paper.
2. In the second stage, the data of the demonstration phase have been used to model a plant on an industrial scale which is called the MARSS module. The MARSS module is based on the same flow chart as the demonstration plant, with the difference of a continuous mode of operation. With 65,000 Mg/a and an hourly throughput of 20 Mg the throughput is twice as high as in the demonstration plant. Since the MARSS module is designed as an add-on for existing MBTs, it will not interfere with the structure of MBT plant processing. For the MARSS module a separate building and own personnel have been scheduled. Thus, the system can operate independently. After all, only one feeding line connects the MBT with the MARSS module (see Fig. 2).

Based on the two project stages, a holistic evaluation of the MARSS process is possible by answering the below listed process, product and economic issues.

Process- and product-specific issues:
1. Is it possible to produce a biomass fuel by fulfilling the main fuel requirements?
2. What are the mass flows of the products and inside the plant?
3. What are the main requirements on the MARSS input material for post-treatment?

Economic-specific issues:
4. What are the costs for the MARSS module?
5. Under which circumstances is the investment into the MARSS module worthwhile?

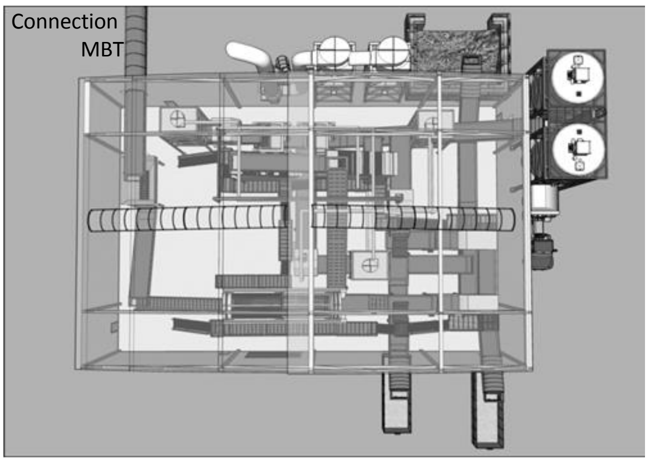


Fig. 2 Picture of the MARSS demonstration plant (left) and the MARSS module (right)

2.3 Process description of the demonstration plant and the MARSS module

The machine technology of the MARSS demonstration plant follows a basic scheme based on processing objectives and can be divided into the following five parts (see Fig. 3).

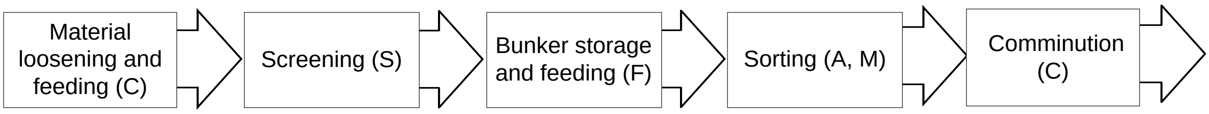


Fig. 3 Basic process scheme of the MARSS demonstration plant

With help of the flow chart in Fig. 4 the basic scheme as well as the objectives of the single process parts (each process is assigned a number, e. g. C 1) can be explained as follows:

Process part C aims, on the one hand, at loosening and feeding the dried MMSW input material (C 1) to the MARSS plant and, on the other hand, to decrease the upper grain size in the fuel below a maximum value of 30-40 mm (C 2). This is necessary, because large elongated particles[2] may block the dosing screw of the combustion plant. C 1 is followed by screening. The objective of the first screening (S 1) is to accumulate biomass in the screen underflow. The following screenings (S 2-3) achieve narrow grain size bands necessary for the subsequent sorting processes. The third process part (bunker storage and feeding, F), which is only part of the demonstration plant, consists of a dosing bunker system. This bunker system was used to store and feed the material for a batchwise sorting on the air sifter. Air sifters (A 1-3) then sort impurities (inert and fossil material) out of the biogenic fuel. The MARSS plant also includes metal sorting (M 1-4), which aims at separating the valuable metals from the residual flows. Metal separation is an optional process since it is not necessary for the production of RRBF. In many cases it is worthwhile to install a metal sorting due to the economic values of metal products. The processes of the demonstration plant are explained in detail in Chapter 3.

As mentioned, the MARSS module operates continuously and all machines are designed for an industrial scale, which corresponds to twice the throughput of the demonstration plant. During operation of the demonstration plant, potentials for process optimization have been ascertained and, thus, are implemented in the MARSS module. The flow diagram of the module is essentially comparable to the demonstration plant. In Fig. 4 the flow chart diagram of the MARSS module and the demonstration plant is shown, in which the differences are marked.

[2] Although the material is screened at 40 mm there are particles which are larger than 40 mm in the screen underflow. Particles that are smaller than 40 mm in two dimensions can pass through the screen openings if their third dimension is greater than 40 mm.

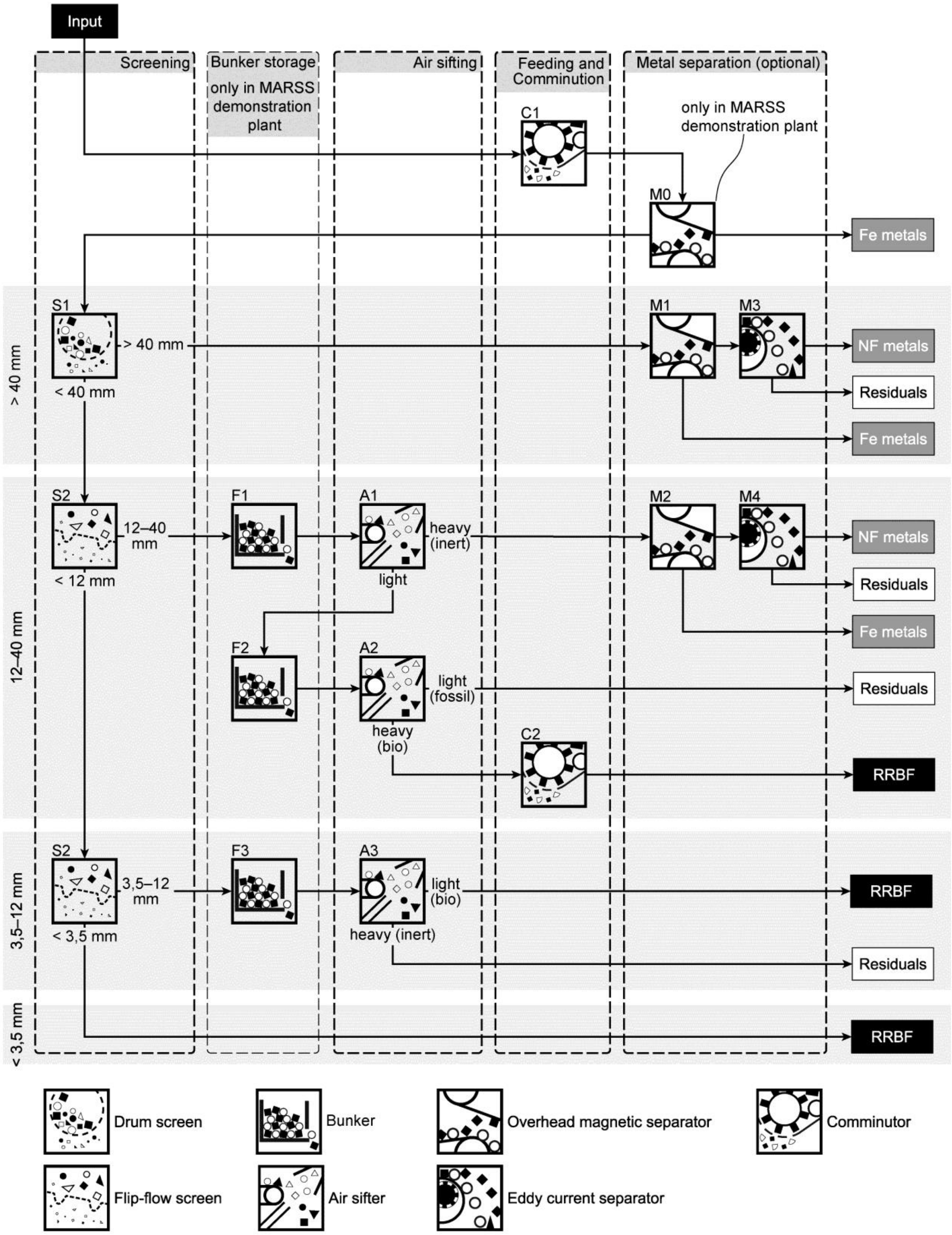


Fig. 4 Flow chart of the demonstration plant and the MARSS module

2.4 Test campaigns and analysis

The results presented in the next chapter are based on different test campaigns which were carried out during the demonstration phase in order to test and optimize the process and specific parameter settings of the plant. Moreover, three large combustion tests (fuel tests) of the produced RRBF were carried out at UMSICHT, a Fraunhofer Institut in Oberhausen, Germany. UMSICHT utilized the suitability of RRBF for combustion in a 100 kW combustion testing unit based on fluidized bed technology. The tests confirmed that the RRBF is a suitable fuel for small CHP plants. Details on these tests can be found in literature [31].

Depending on the different investigation targets of the test campaigns the sampling scope was determined. Volume, mass and number of samples were chosen considering the requirements of LAGA PN98 (guideline for the procedure of physical, chemical and biological analysis regarding recycling/disposal of waste) [32]. The hence generated different samples were evaluated in terms of composition (DIN EN 15440:2011 [33]), calorific value (DIN51900 [34], RAL GZ 724 [35]), water content (DIN EN 14774 [36], DIN ISO 11465 [37]), ash content (DIN 14775 [38]) and mass distribution. Currently no standard quality for biomass fuels out of MMSW is defined by the EU. Nevertheless, the objective of the project was to reduce the fossil content as far as possible (cf. requirement R3). Therefore, the fossil content of the samples needs to be analysed. The common practice in research is to analyse by manually sorting only the coarse fractions (e. g. > 10 mm in accordance with DIN EN 15440:2011 [33]) and to summarize the not further analysed fine fractions as "residuals", "remaining" or "fine" [2]. However, the very high content of small and very small particles of the MARSS input material (~65-70 wt. % < 40 mm; ~30-35 wt.-% < 12 mm) required a more precise analysis. Thus, following the "Methodological manual for analysing organic fertilizer, soil improvers and substrates" of the "Federal Compost Quality Association" [39] the material was manually sorted using tweezers. The fossil materials were thereby sorted out of the grain size fraction of 3.5-12 mm. The smaller fraction of 0-3.5 mm was analysed by examining fossil, biogenic and inert reference samples under the microscope. Almost no fossil material was found in this fraction. Based on the findings the percentage of fossil material in the fraction of 0-3.5 mm was set to 0 wt.-%, and the fraction was counted as biogenic. The disadvantages of this method are the high sorting effort and the higher "subjective error potential" as finer grains are more difficult to distinguish. In addition, the manual sorting results were evaluated using the costly 14C-method in accordance with DIN EN 15440:2011 [33]. Comparing the two methods, the analysis results of the reference samples were almost similar (±1 wt.-%). Due to comparable analytical results and the expensive C14-method, the fossil content was determined using the manual sorting method. The selective dissolution method was not suitable because of high content of fats, coals etc. in the fine waste fractions that lead to an incorrect measurement (cf. DIN EN 15440:2011 [33]).

3 RESULTS OF THE DEMONSTRATION PHASE

The previously mentioned processes and process parts of the demonstration plant were tested and optimised during the plant operation. This chapter presents the most important parameter settings and findings of the demonstration phase. They can be utilized to reproduce the results of the demonstration plant in similar circumstances. This transferability may be limited under deviating conditions. (e. g. differences in the waste composition due to regional factors, cf. Chapter 2.1).

3.1 Screening

As described in the flow chart in Fig. 4, three screens had been installed in the MARSS plant, namely a drum screen and two flip-flow screens. The three objectives (O) of screening are

O 1. to divide the material flows for the subsequent sorting processes into suitable, narrow particle size bands. For an effective air sifting, the ratio between the maximum and minimum particle size should be around 3/1-4/1. Hence, the grain size fractions 3.5-12 mm and 12-40 mm generated with the MARSS screens are well suited for the following sifting processes.

O 2. to divide large mass and volume flows, whereby an appropriate dimensioning of the subsequent sorting machines can be realized.

O 3. to enrich or deplete certain groups of materials in certain grain size distribution ranges (cf. the different compositions of the two fractions generated by the drum screen (Fig. 6).

3.1.1 Drum screen

Fig. 5 shows the drum screen that was used in the MARSS plant. Drum screens are dynamic screening machines and are assigned to the revolving screen category. The coat of a drum screen represents the screen lining. The screening drum is usually set into rotation by wheels or chain drives. The filling volume is of great importance for dimensioning the drum screen and should be at about 15 vol.-%. Through friction and centrifugal forces of the rotating screening surfaces, the material is drawn upwards. Above a certain altitude gravity compensates frictional forces and the particles fall back downwards. The constant circulation ensures that most particles that are smaller than the screen openings pass through. Through an inclined drum body of about 3 ° to 6 ° the material simultaneously moves forward. An advantage of this screen type is the good cleaning of fine material and the homogenization by the frequent material circulation. [11, 40]

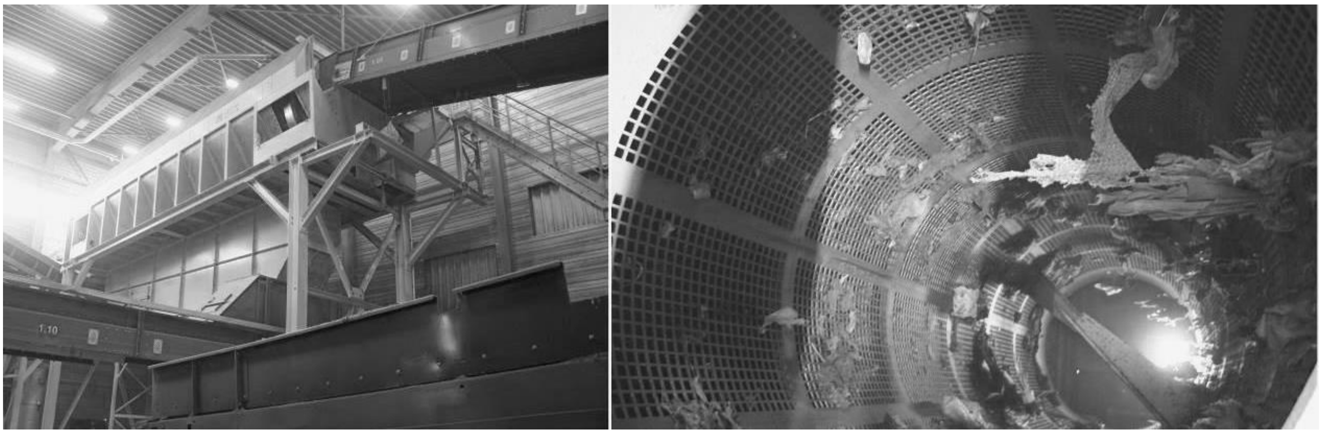


Fig. 5 Drum screen of the MARSS plant

Drum screens are used for the classification of wastes containing a high proportion of large-scale particles, such as foils, other plastics or textiles. For that reason, a drum screen was used as the first screening stage in the MARSS plant to remove the majority of plastics and plastic compounds with the screen overflow and to enrich the biogenic materials in the underflow (O 3). Fig. 6 depicts a mass balance and the average material composition of the different grain size fractions. Due to the low biogenic share the screen overflow is not processed further into biomass fuel. It can either be burned as RDF (net calorific value approx. 16,000 kJ/kg), be further processed (e. g. plastic recycling) or landfilled (in accordance to national directives[3]). The biogenic enriched screen underflow, however, will be further processed as biomass fuel. Therefore, the screen underflow will be screened at 12 mm and 3.5 mm using flip-flow screen technology.

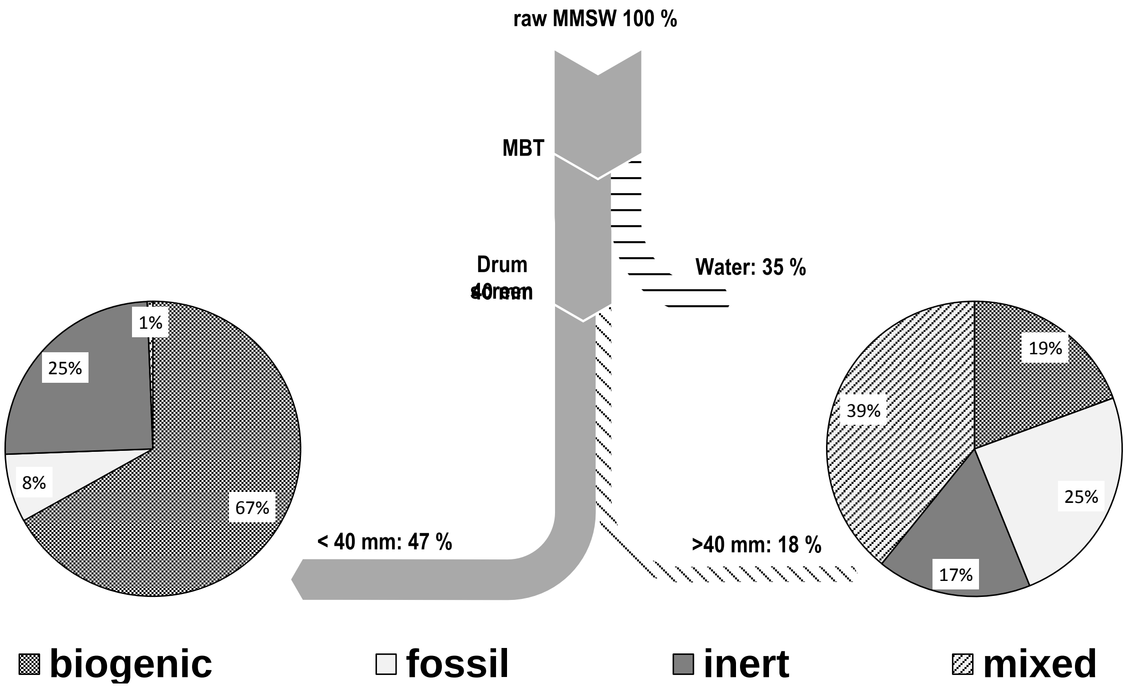


Fig. 6 Mass balance of the first screen and the drying process

[3] For instance, in Germany this is not allowed because of the strict requirements of the German Landfill Directive [41].

3.1.2 Flip-flow screen

Flip-flow screens are also dynamic screens and represent a special type of throwing sieves. Fig. 7 shows the flip-flow screen used in the MARSS demonstration plant and in addition a schematic structure of that screen.

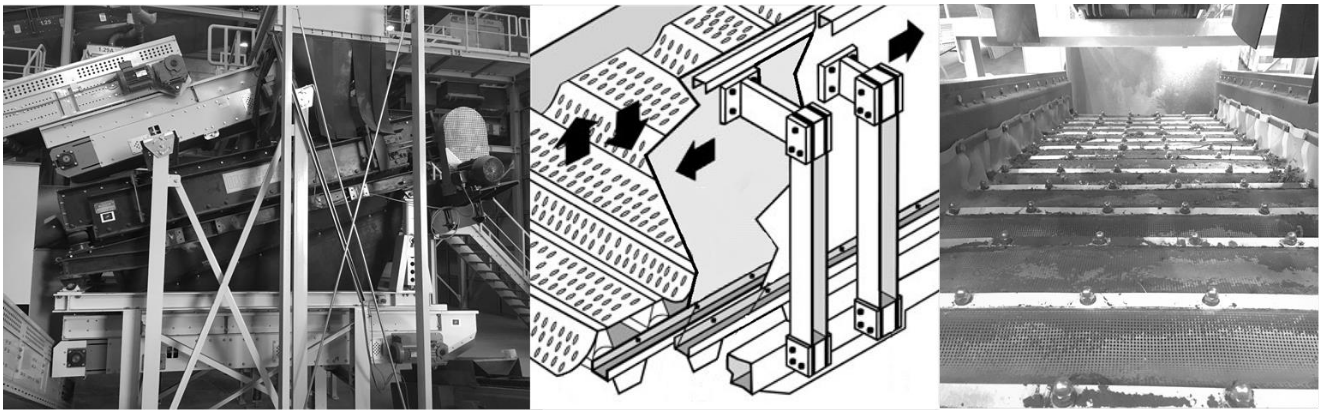
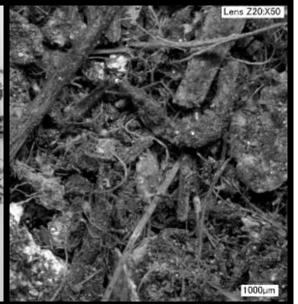
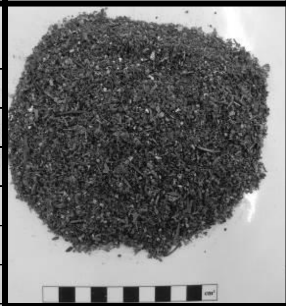
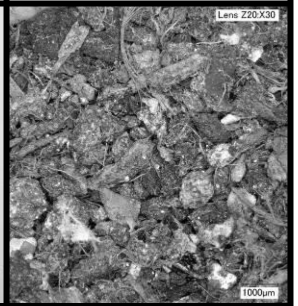


Fig. 7 Flip-flow screen 2 of the MARSS plant, schematic structure due to [11]

The flip-flow screen consists of two units, a stationary screen box with fixed crossbars and a flexible carrier system with crossbars. The flexible polyurethane screen mats are each mounted between a fixed and a flexible crossbar. An eccentric shaft moves the flexible unit, thereby causing a relative movement between the systems, alternately stretching and relaxing adjacent screen mats. When stretched, the mats throw the material upwards with an acceleration force of up to 50 G. Upon hitting the screen mats the material can pass through the openings. The probability of fine grain passing through the screen openings will raise as the contact between grain and screen mats is increased. The screen inclination angle and the screen lengths affect the dwell time of the material on the screen. Due to the high acceleration forces throwing the feed material, flip-flow screens are used for material that is particularly difficult to screen. Fine-grained, moist and fibrous materials fall into this category. [11] In the MARSS plant, examinations of the drum screen underflow (0-40 mm) showed that it consists mostly of very fine (~50 wt.-% are less than 10 mm), biogenic [42], fibrous material (photo of the fractions can be seen in Table 1). Consequently, the material in the MARSS plant is screened using two flip-flow screens at 12 mm and 3.5 mm for generating narrow grain bands (O1). Moreover, a dust fraction of 0-3.5 mm is separated, which is too fine for effective sorting by air sifter. Furthermore, the fossil content of the fraction 3.5-12 mm is below 2 wt.-% so that no further separation of the fossil materials from this grain size fraction is necessary [42]. The main parameter settings are listed below in a tabular form for each screening unit (Table 1). For a better understanding of the process, the most important parameters and their impacts are discussed later on.

Table 1 Screen parameterization

screening machine	objective/Comment	parameter		material photos	
	Enrichment of biogenic material in screen underflow Removing fossils out of screen underflow	type	SR 7.5/2.3		
		screen opening	40 mm		
		throughput	~8-10 Mg/h		
		inclination	3°		
		rotating speed	20-50 Hz		
		screen length	7.5		
drum screen		drum diameter	2.3	12-40 mm	> 40 mm
	Preparation for air sifting (narrow grain size band) Removing fossils out of screen underflow	type	LIWELL® LF 1.5-5.04/16 ED		
		screen opening	12 mm		
		throughput	~5.6-6.7 Mg/h		
		useable screen area	7.56 m^2		
		useable screen length	5.040 mm		
		inclination	33°		
		screen cut 50%	8.1 mm		
flip-flow screen 1		screening capacity η	87.3 %	3.5-12 mm	microscope
	Preparation for air sifting (narrow grain size band) Removing of dust out of screen overflow for air sifting	type	LIWELL® LSF 1 - 14		
		screen opening	3.5 mm		
		throughput	~2.7-3 Mg/h		
		useable screen area	3.59 m^2		
		useable screen length	3.125 mm		
		inclination	27°		
		screen cut 50%	1.9 mm		
flip-flow screen 2		screening capacity η	76.5 %	0-3.5 mm	microscope

3.1.3 Screen cut point

In this paper and for the figures, the nominal screen opening of the flip-flow screens is used. The nominal screen cut complies with the dimensions of the tool the screen mats were perforated with. However, the flexible flip-flow screen mats (see Fig. 7 right side) are made of elastic polyurethane. Depending on the alternating stretching and relieving of the screen mats, the screen openings can widen or narrow. The effective screen cut point is therefore dynamic and different from the nominal screen opening. Thus, the effective screen cut was determined for the MARSS plant. It is assumed that the effective screen cut equals the diameter where both screen overflow and underflow consist of 50 wt.-% of the feed material. Based on grain size distributions, the separation function ($T_{(x)}$) can be set up. The separation function for the second flip flow-screen is exemplary presented in Fig. 8. Using this function the screen cut point 50 % (in the example at ~1.9 mm, dark dashed line) can be determined. Generally, the following applies: nominal screen opening > effective screen cut point.

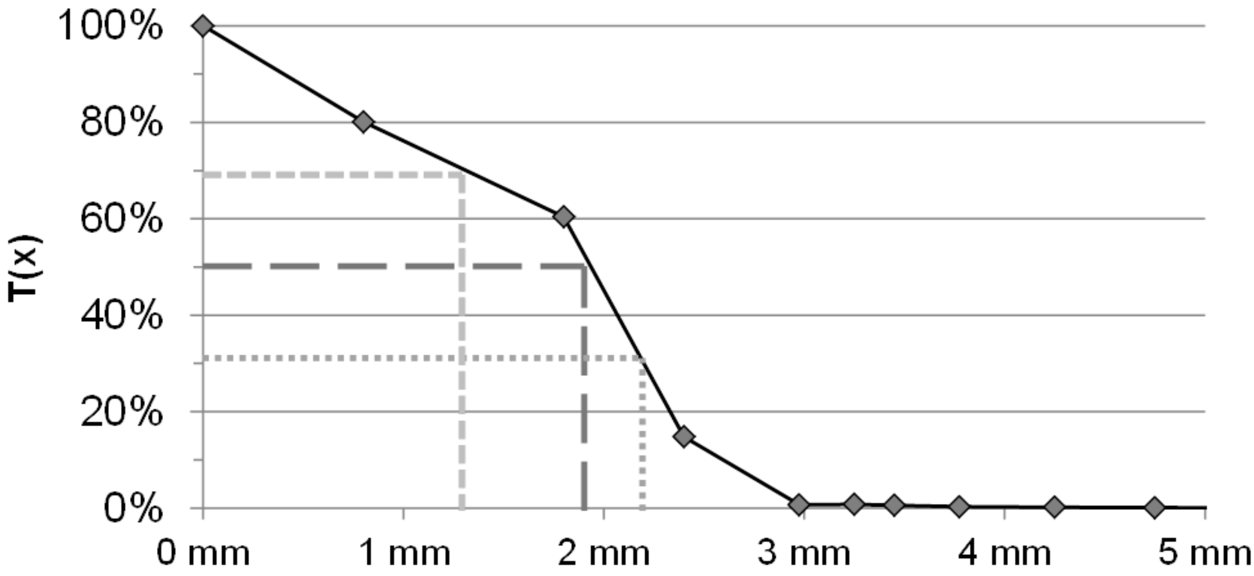


Fig. 8 Separation function of flip-flow screen 2 (nominal screen opening of 3.5 mm)

3.1.4 Screening evaluation

The success of screening can be determined by the screening capacity. The screening capacity indicates how much fine material remains in the screen overflow albeit being smaller than the screen openings [43].The screening capacity was determined for the effective screen cut point and amounts to 88% for screen 1 and 76% for screen 2.

3.1.5 Water content

The screening capacity depends on the water content, as it is the case for all technical separation processes. During the demonstration plant operation, the influence of the water content on the screening results became evident. As an example, Fig. 9 shows grain size distributions of fine[4] waste at different water contents.

[4] Looking at the flow chart in Fig. 4 the screen underflow (0-12 mm) of the flip-flop screen (S 2) was utilized.

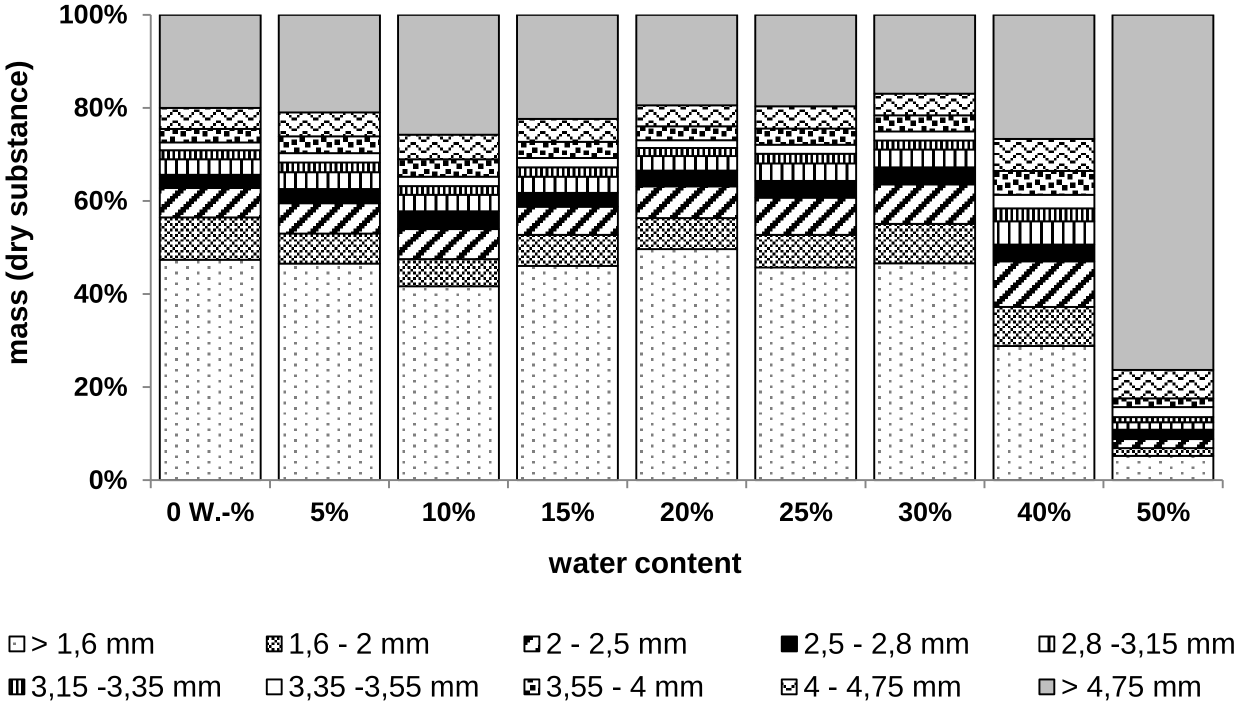


Fig. 9 Influence of water content due to the grain size fractions

From a water content of about 30 wt.-%, the share of coarser grain sizes increases, whereas the finer grain fraction shares fall. This is due to the increased agglomeration of particles above this water content. As an example, Fig. 10 shows images of agglomerates which are formed at a water content of 50 wt.-%. Individual fine grains are barely visible.

Fig. 10 Agglomeration of fine grain due to a water content of 50 wt.-%

Fig. 11 shows the mass recovery in the screen underflow and the screening capacity referring to the water content. At a water content of 30 wt.-% and higher, less fine fraction is recovered in the screen underflow. The screen capacity decreases accordingly.

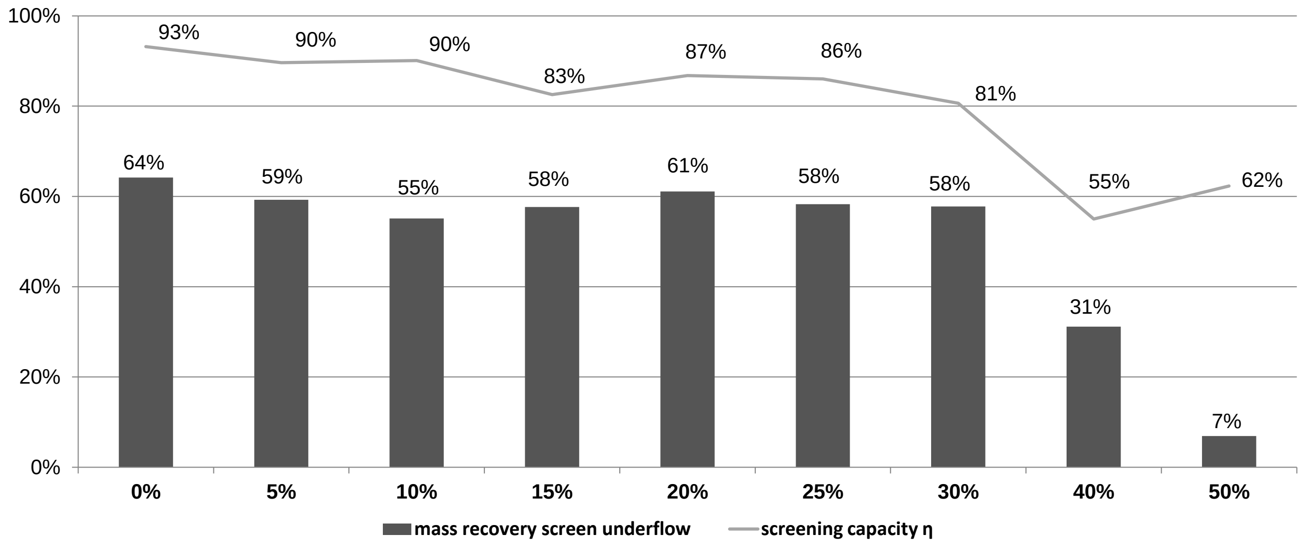
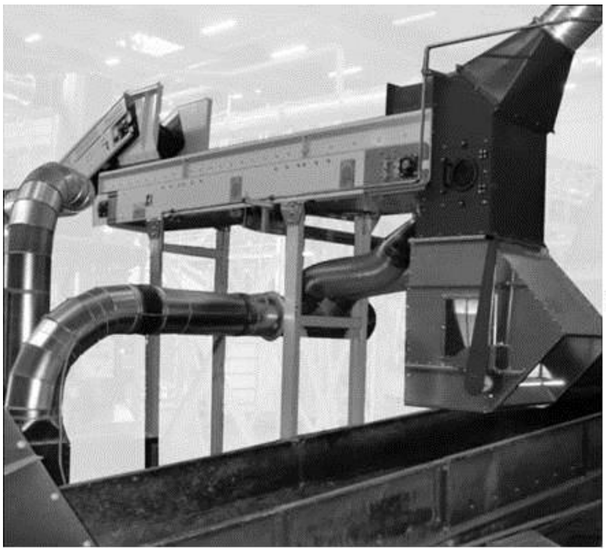


Fig. 11 Mass recovery and screen capacity depending on the water content

3.2 Air Sifting

The aim of the air sifting is to separate biogenic material from inert material and fossil plastic. These three materials have different characteristics, enabling to separate them in an air sifter (by their density, grain size and shape). The separation of the different materials is only possible in two consecutive sifting processes due to the properties of the particles. As seen in Fig. 4, the grain size fraction of 12-40 mm is at first treated to remove the inert material. Afterwards, the fossil plastic foils are sorted out. As mentioned, the fossil content in the grain size fraction of 3.5-12 mm has been reduced by screening to less than 2 wt.-%. Therefore only the inert material has to be removed out of this fraction using an air sifter. The high content of fine materials influences the air sifting efficiency. To achieve better sorting results the air sifter used in the MARSS plant was modified by adding an arcuate baffle inside the sifter channel (see schematic in Fig. 12). Supported by the baffle the material stays in the air flow for a longer time period whereby a better sorting performance is achieved. Fig. 12 shows the air sifter that was used together with a schematic illustration. The different materials are sorted in the sifter based on their settling velocity in the air stream. In case the settling velocity is greater than the air velocity, the material falls downwards against the air flow and is discharged in the heavy fraction. However, in case the air velocity is greater than the settling velocity, the material is transported upwards with the air stream, before it is separated from the air by means of a cyclone. This material is called light fraction. The cyclone air is filtered from dust and recirculated to the ventilator.



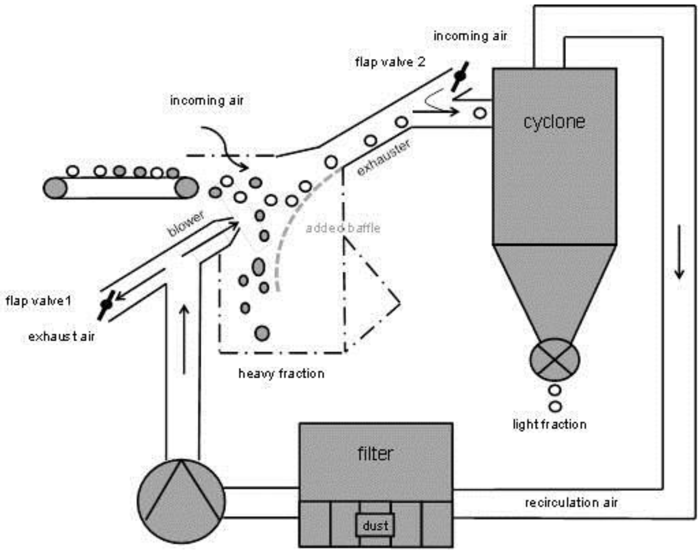
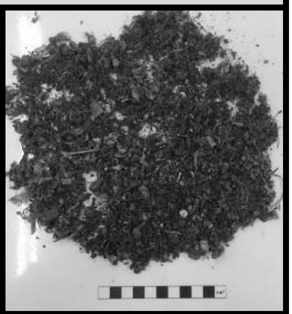
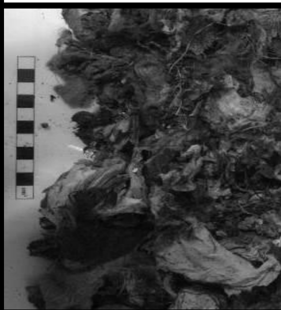
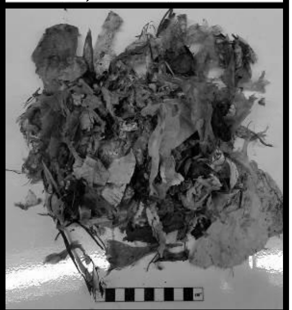


Fig. 12 Air sifter of the MARSS plant (left) and its schematic illustration (right)

In general, the stationary velocity depends on the density of the material, the grain size and the grain shape/surface. The main distinguishing feature between inert material and biogenic material is the density. Due to the influence of the grain size, it occurs that “large and light” particles behave the same as ”small and heavy” particles inside the air sifter. Since the MARSS project, however, focuses on separating the material based on density, the influence of the grain size was minimized by screening and narrowing the grain size band (mentioned as screen O1). The heterogeneity of the waste material, interparticle forces, the turbulence of the air flow and other influences cause the misplacement of particles. Therefore, it is not possible to assume a consistent product quality. To minimize the amount of misplaced materials, the parameter settings of the MARSS air sifters have to be determined based on the feed material. During the demonstration operation, the parameters with significant influence have been identified and the air sifter has been set accordingly. Table 2 shows the default settings of the air sifter. During the demonstration phase, however, the parameters were partially adjusted.

Table 2 Air sifter parameterization

fraction and objective	**parameter**		**material photos**	
3.5-12 mm reduction of inert material	inlet air [m³/h]	~ 6000		
	air loading [kg/m³]	0.1-0.2		
	valve 1 [% closed]	33 %		
	valve 2 [% closed]	100 %		
	air blower	45-50 Hz		
	air velocity channel	~ 13 m/s		
	air velocity pipe	~ 24 m/s		
	nozzle inclination	54°	heavy fraction (inert)	light fraction (biogenic)
12-40 mm reduction of inert material	inlet air [m³/h]	~ 7000		
	air loading [kg/m³]	0.2-0.3		
	valve 1 [% closed]	33%		
	valve 2 [% closed]	100%		
	air blower	55 Hz		
	air velocity channel	~ 16 m/s		
	air velocity pipe	~ 26 m/s		
	nozzle inclination	54°	heavy fraction (inert)	light fraction (biogenic + foils)
12-40 mm reduction of fossil foils	inlet air [m³/h]	~ 5000		
	air loading [kg/m³]	0.2-0.3		
	valve 1 [% closed]	0 %		
	valve 2 [% closed]	0 %		
	air blower	40 Hz		
	air velocity channel	~ 5-6 m/s		
	air velocity pipe	~ 20 m/s		
	nozzle inclination	54°	heavy fraction (biogenic)	light fraction (fossil foils)

3.2.1 Air velocity

The main parameter for the air sifter is the air velocity in the sifter channel. The air velocity is controlled, on the one hand, by the air blower and, on the other, by the air flow in the air sifter. In front of and behind the air sifter channel, air can be added or removed from the circulation by adjusting specific flap valves (see schematic illustration in Fig. 12). By closing flap valve 1 before the air sifter channel more air is directed to the nozzle increasing the blow rate. By closing air valve 2 behind the channel more air is sucked out of the channel and the suction speed increases. The air velocity in the air sifter is crucial for the material sorting and has been approximated for the demonstration plant by using a Prandtl tube and an impeller anemometer. Due to the turbulent flow conditions in the air channel, air velocity can only be estimated, since both instruments are designed for a laminar flow. In Table 2 an approximation value is therefore used for the air velocity. Furthermore, the air blower settings (frequency) and flap valve aperture (%-closed) are given in the table. Five measurement points (MP) were placed over the course of the air channel in order to measure the air flow. Fig. 13 shows the course of the air velocities of the five metering points at four different parameter settings. Apparently air velocity decreases between the nozzle and the exhaustion socket. The air velocity given in Table 2 was carried out at metering point 3 which is the intersection of the ballistic material parabola and the air flow.

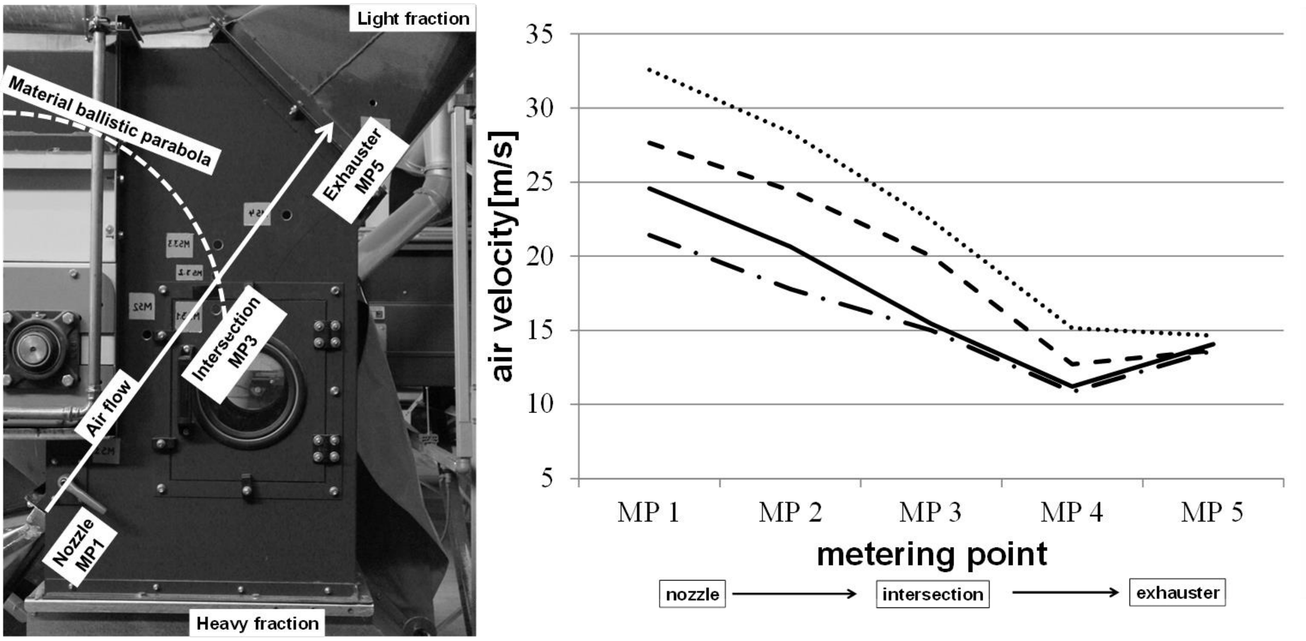


Fig. 13 Air velocity inside the sifter channel

3.2.2 Nozzle inclination

In addition to air velocity, the air flow can be changed by adjusting the nozzle inclination. In the demonstration operation, however, this setting has not been changed. According to the manufacturer, the nozzle should be directed in the upper third section of the air exhaustion socket, which equals an inclination angle of 54 ° in the MARSS plant.

3.2.3 Water content

During the demonstration operation the water content of the feed material has been identified as a major factor on the success of the air sifter. The biogenic material stores more water than the inert and fossil material. Consequently, the density of the biogenic material increases with increasing water content. As a result, a higher share of biogenic material is transferred into the heavy fraction. Fig. 14 shows the influence of the water content for grain size fraction of 3.5-12 mm at unaltered parameters of the air sifter. It can be seen that the higher the water content, the more mass is separated into the heavy fraction. When comparing the results for a water content of 10 wt.-% and 30 wt.-%, the biomass in the heavy fraction increases from 5 wt.-% to about 55 wt.-%. As a result, the recovery of biomass decreases from 98 wt.-% to 70 wt.-%.

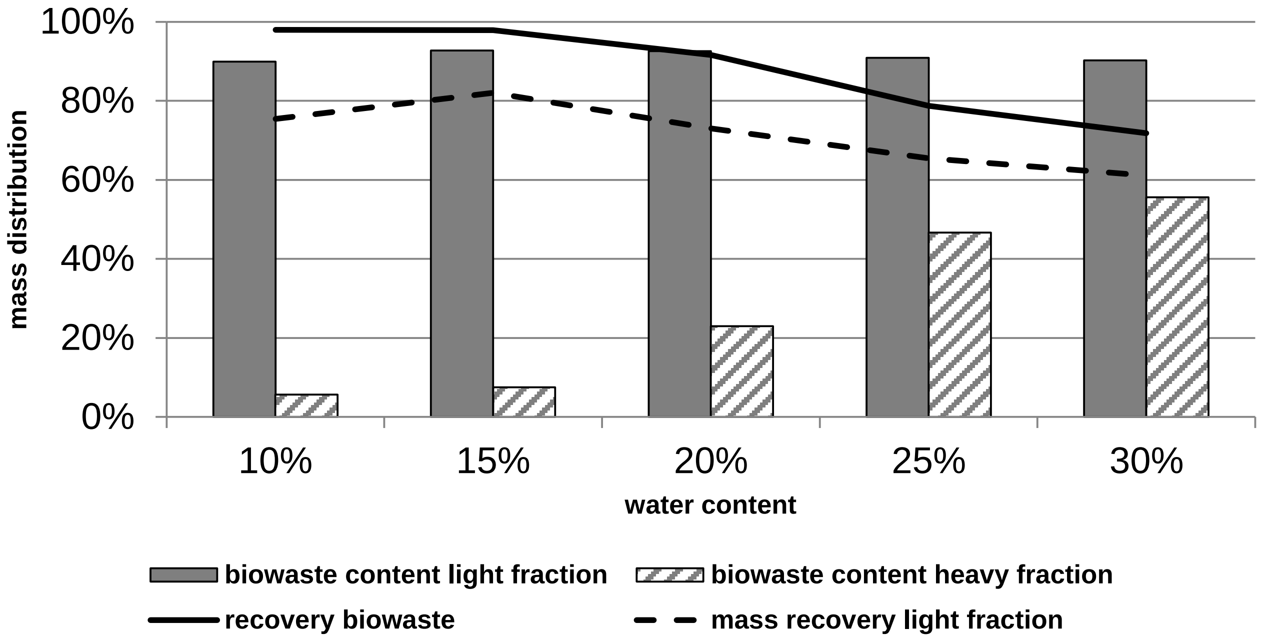


Fig. 14 Sorting efficiency of air sifter in dependence of the water content

At best, the water content of the feed should be below 15 wt.-% for an effective sorting process. At higher water contents, the air velocity must be increased. In this case, however, more inert material passes into the light fraction, which increases the ash content and decreases the net calorific value of the biogenic material in addition to the reduction that is already caused by the higher water content. Good drying results of the MBT prior to sorting are therefore necessary.

3.2.4 Air load

According to Kranert, the mass-air-loading number for effective sorting in the air sifter should be below 0.35 kg/m³ air [11]. A higher mass-air-loading number could lead to the interparticle forces viz. neighbouring particles hinder one another in their trajectory. The finer and lighter the material, the more particles are present to interfere with one another in their trajectory. During the demonstration operation the interparticle forces were strongest at the fine grain size 3.5-12 mm. While the mass-air-loading number for the coarser grain size of 12-40 mm was chosen between 0.2-0.3 kg/m³, it had to be decreased for the finer grain size fraction to 0.1-0.2 kg/m³.

3.3 Metal separation

Metal recovery is not a primary goal of the MARSS project, however, recovering the metals from the residues can improve the overall profitability. The main task is to generate a metal product of positive market value. A compromise between recovery and purity of recyclable material in the product has to be found.

According to the flow chart in Fig. 4 three fractions were identified for a worthwhile metal separation: The demonstration plant input, the fraction > 40 mm and the heavy fraction of the grain size fraction 12-40 mm. The plant input is treated by an overhead magnetic separator to recover coarse ferrous (Fe) metals. This process is only part of the demonstration plant and can be omitted for the MARSS module, as the majority of the metals would also be sorted out within the two other fractions. The > 40 mm and the 12-40 mm fractions are treated by a combination of an overhead magnetic separator and an eddy current separator to recover both ferrous and non-ferrous (NF) metals. For the results provided in Table 3, the MARSS plant is considered as a whole combining all three fractions.

Table 3 Results of metal separation

	ferrous metals	non-ferrous metals
concentration of recyclable metals in the product	84 wt.- %	66 wt.-% (including composites with paper/lightweight plastics) 56 wt.-% (excluding composites with paper/lightweight plastics)
yield of recyclable material	66 wt.-%	77 wt.-% (including composites with paper/lightweight plastics) 74 wt.-% (excluding composites with paper/lightweight plastics)
recovery of mass, based on the dried input material	3.0 – 3.5 wt.-%	1.0 – 1.2 wt.-%

3.4 Drying (MBT)

Numerous water content analyses were carried out during the project operations due to the great influence of the water content on the processing and the RRBF. As mentioned above, effective drying of MMSW is a prerequisite for a successful post sorting of the MBT output in the MARSS plant. A high water content reduces the screening and sorting performance of the plant as well as the net calorific value of the fuel. To achieve good results, the water content of the input material of the MARSS plant should be below 15 wt.-%. Furthermore it was measured that finer grain sizes possess a higher water content. The highest water content is found in the grain fraction 0-3.5 mm. Fig. 15 shows the water measurements results for the grain size fraction 3.5-12 mm in 2015.

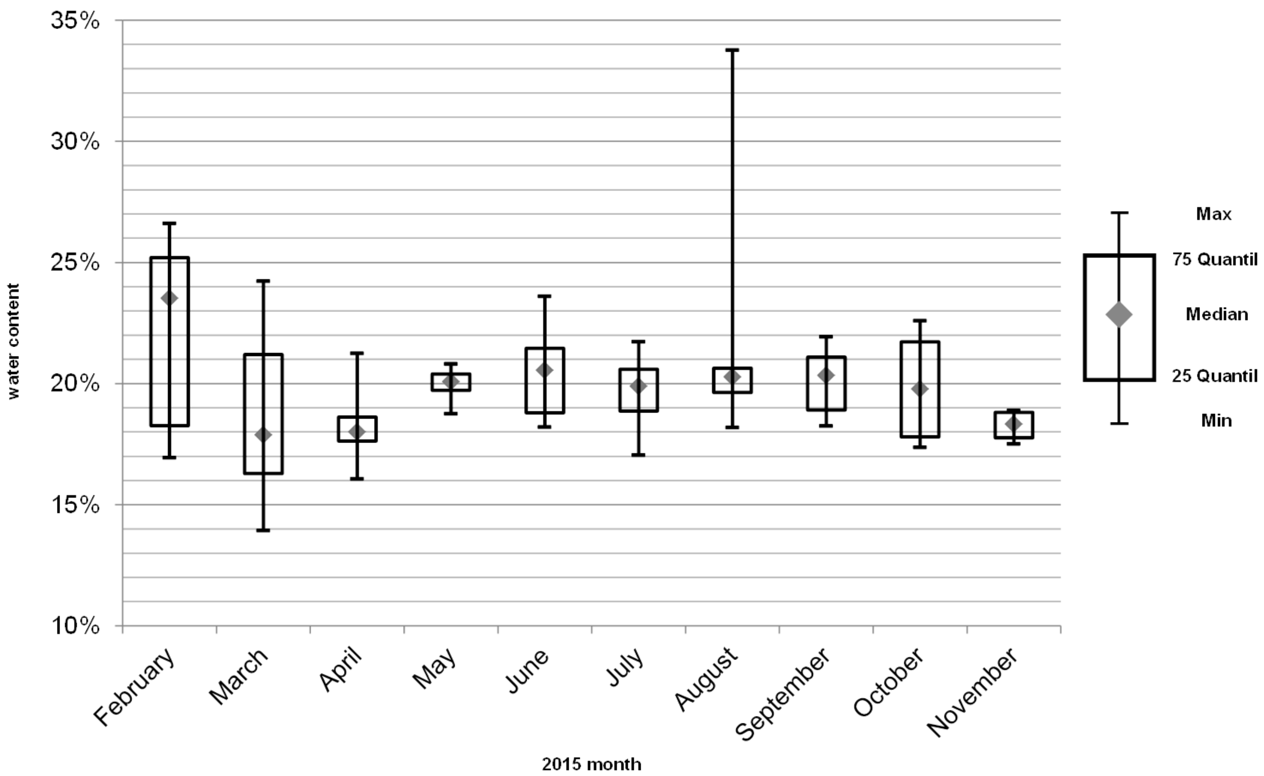


Fig. 15 Water content measurements of the fraction 3.5-12 mm

In February, the drying boxes were cleaned and thus the water content was on average higher than after cleaning. Neglecting the data of February, increased water content can be observed in the summer, which is, amongst others, due to the higher saturation of warm summer air. The measurement results also show significant outliers. For example, the average water content in August 2015 was about 20 wt.-%, while a single value of almost 35 wt.-% was measured in that same month.

4 CONCLUSION

Bearing in mind the previously formulated process- and product-specific issues, the following results are summarized:

1. *Is it possible to produce a biomass fuel by achieving the main fuel requirements?*

The RRBF was produced using the mentioned process flow chart in Fig. 4. Approximately 42 wt.-% (ar[5]) of the MARSS input material could be recovered as RRBF. Fig. 16 shows the material composition of the dried input material and the RRBF output for the third fuel test campaign. The biogenic content[6] could be enriched from 50 % to over 90 % by mass. The net calorific value of the RRBF varies between 10 and 12 MJ/kg. It has an ash content of about 27 wt.-% (D[7]). The fossil content is below 10 wt.-%(~6-9 wt.-% ar). Moreover, 70-75 wt.-% of the biological materials in the MARSS input were recovered in the RRBF output. As a result, the project requirements, mentioned in Chapter 2.2, were achieved.

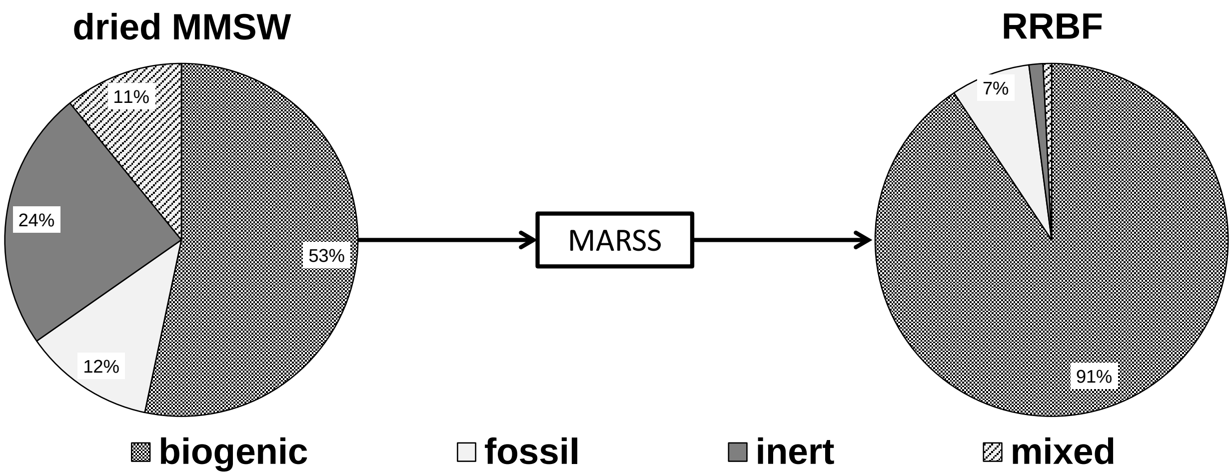


Fig. 16 Input and output material composition of MARSS

2. *What are the mass flows of the products and inside the plant?*

A mass balance was created based on the data collected in the MARSS demonstration plant. For example, the mass balance of the third fuel test campaign is shown in Fig. 17. In this fuel campaign a mass recovery of about 28 wt.-% based on the MBT input and about 43 wt.-% based on the MARSS input could be achieved.

[5] ar = as received = original substance with water
[6] The grain size fraction 0-3.5 mm was counted as 100 % biogenic material (cf. analytical method).
[7] D = dry substance, dried in order to DIN EN 14774

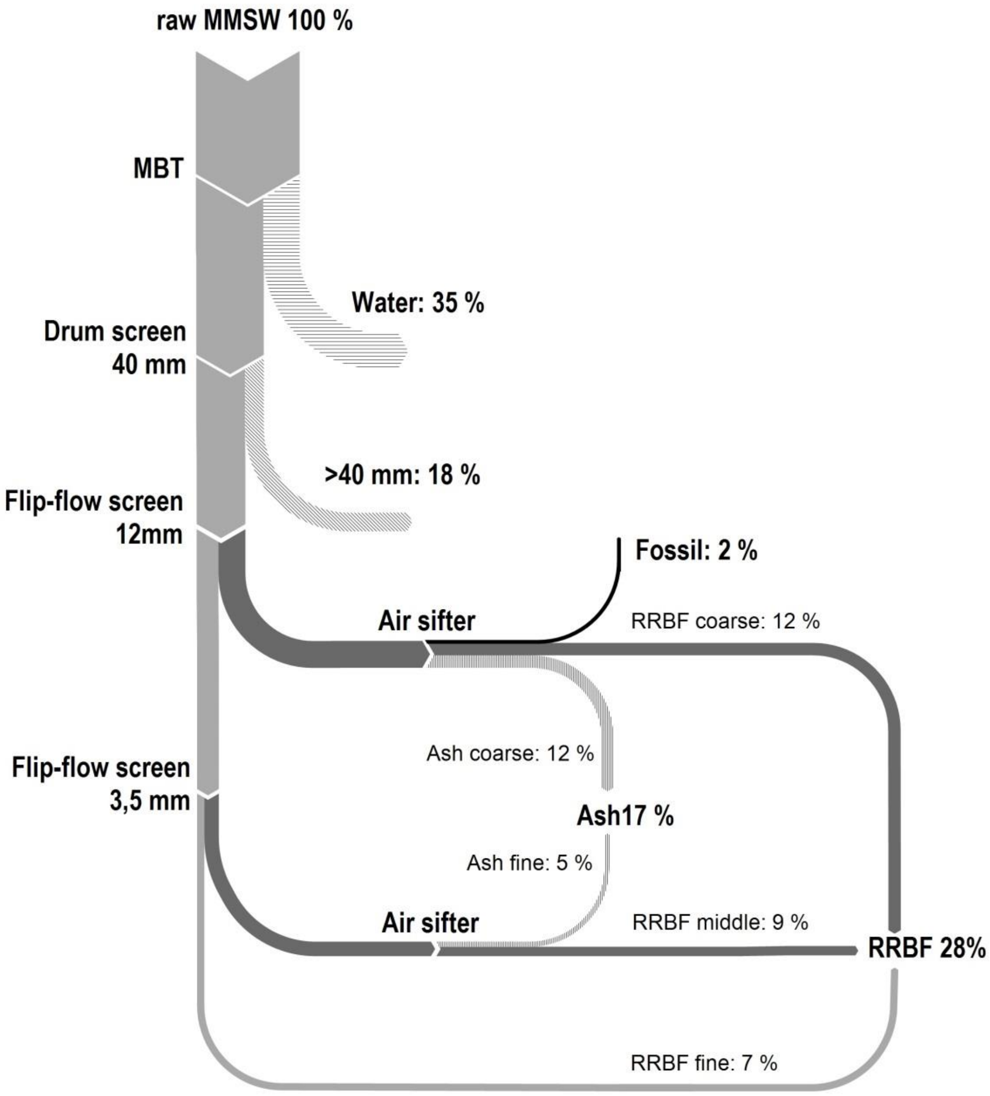


Fig. 17 Mass balance of the third fuel test campaign

3. *What are the main requirements on the MARSS input material for post-treatment?*

Successful screening and sorting are, above all, dependent on effective material drying in the MBT. The screening capacity, for instance, decreases greatly with water contents of 30 wt.-% and above. Moreover, the sorting capacity already decreases significantly at a water content of 15 wt.-%. That is why a high drying rate of the MBT is a main requirement for a successful post separation via MARSS. Hence, the MARSS input material should have water contents of 15-20 wt.-% or less.

4.1 Mass balance of the MARSS module

Looking at the mass balance, it is important to consider that the mass recovery and fuel quality (calorific value, fossil content) fluctuate and are dependent on different parameters:

- Local and time parameters: e. g. waste composition, seasonal fluctuation
- Technical parameters: e. g. selection of screen cut, air sifter velocity and calibration, drying, screening and sorting efficiency

For this reason, in addition to the current average RRBF production the fluctuation of RRBF is shown including best and worst case scenarios (see Table 4).

Table 4 Mass balance MARSS module

100,000 Mg/a MSW

↓

MBT	
working days per year	250 d/a
throughput/day	400 Mg/d
dry mass lost	35%
MBT output	260 Mg/d

↓

MARSS module	
net working hours in a two shift operation	13h/d
bulk density	250 kg/m³
hourly throughput	20 Mg/h 80 m³/h

↓

RRBF	
	average (best / worst)
mass Mg/h	**8.5** (9.2 / 7)
mass %	**42.5** (46 / 35)

residuals				
average	RDF/landfill	Fe-metals	NE-metals	landfill
mass Mg/h	5.8	0.7	0.2	4.8
mass %	29	3.5	1	24

4.2 Economic evaluation of the MARSS module

To evaluate the success of the MARSS module, an economic analysis was carried out (industrial scale: input MBT ~ 100,000 Mg/a, input MARSS ~ 65,000 Mg/a or ~20 Mg/h). The evaluation is summarized by answering the project issues 4 and 5.

4. *What are the costs for the MASS module?*

The first step of the economy analysis is the cost accounting for the MARSS module. Based on the above-mentioned mass and volume balance an assembly plan was created (see Fig. 18, or 3D video on the MARSS website).

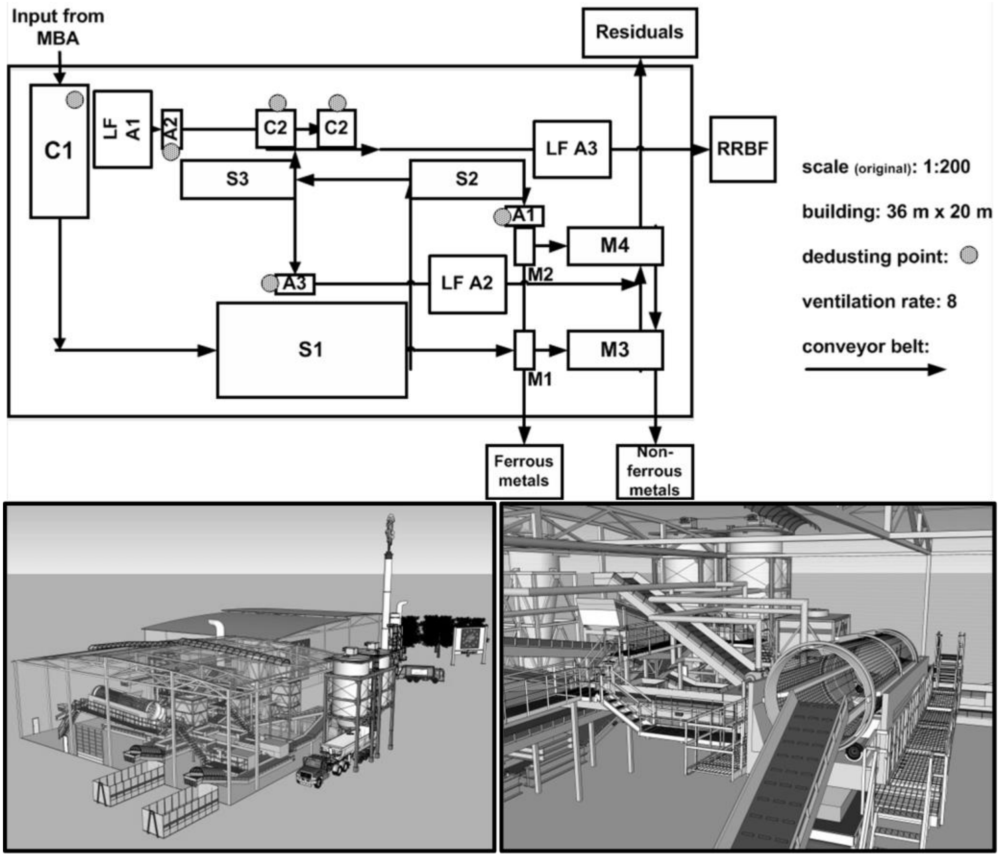


Fig. 18 Assembly plan of the MARSS module in 2D and 3D

On the basis of the assembly plan the equipment dimensions (e. g. throughput/dimensions of machines, number and length of conveyor belts) as well as the building dimensions (~7,200 m³) and related construction equipment (e. g. steelwork and electro technical engineering) were calculated. Subsequently, based on the experience of the project partners pbo (engineering society, Aachen) and I.A.R. (department of processing and recycling, RWTH Aachen University) the M + E (machine technology and electro technical engineering) investment costs were calculated. Furthermore, taking into account construction, services and dedusting, the costs of the building were estimated. Summarized, investment costs for M + E of 3,000,000 Euros and building costs of 1,000,000 Euros were calculated. These amount to capital expenditures of 620,000 Euros/a or 10 Euros/Mg, using the annuity method (interest rate: 3 %, depreciation period: 20 y building and 6 y for M+E). The operating expenditures were at 880,000 Euros/a or 14 Euros/Mg and include personnel costs, maintenance and insurance. Since this is an estimate of costs, a safety factor of 10 % was calculated on the operating costs. Table 5 summarizes the cost calculation. In sum, the overall treatment costs were calculated to about 24-25 Euros/Mg.

Table 5 Overview cost calculation

Investment (for calculation of the capital expenditures)		
structural building components incl. dedusting	1,000,000 €	
M & E (machine technology and electrical engineering)	3,000,000 €	
capital expenditures		
structural building components incl. dedusting	67,000 €/a	1 €/Mg
M & E (machine technology and electrical engineering)	554,000 €/a	9 €/Mg
operating expenditures		
RMS (repair, maintenance, support)	185,000 €/a	3 €/Mg
energy costs	279,000 €/a	4 €/Mg
personnel costs	396,000 €/a	6 €/Mg
insurances, risk etc.		
insurance	23,000 €/a	0.5 €/Mg
administration, risk, contingency	88,000 €/a	1 €/Mg
specific treatment costs		
		24.5 €/Mg

After determining the specific treatment costs a product cost was calculated. For this, prices for processed products have been identified. It should be noted that prices are always dependent on the infrastructural conditions (e. g. number of customers) and the market situation of a region (e. g. supply and demand). As mentioned before, metal sorting is not necessary to produce the biomass fuel as most metals are sorted out with the heavy residual fraction. Nevertheless, the metals sorted within the project achieve high purities and therefore high revenues. The metal/scrap prices are dependent on market situation as well as on the achieved quality (purity). Based on scrap prices, prices for the metal fractions were estimated using a reduction formula to account for the lower purity and further preparation effort of scrap processing. Furthermore, there is currently no market for biomass fuel from residual waste. It is therefore difficult to predict what prices could be obtained for the fuel on the long run. The product costing was conducted using a price of 0-20 Euros/Mg for the RRBF.
The metal and RDF prices were estimated in accordance to the scrap metal prices of October 2015 and the purity of the processed metal fractions.
The specific disposal costs and landfill fees in the EU member countries are very different and have been taken from the table of the Confederation of European Waste-to-Energy Plants [44]. In Table 6 five examples of those different landfill costs and fees in the EU are listed. It also shows the obtained prices for the processed products.

Table 6 Product cost calculation

fraction	**costs / revenues**	
RRBF		0 - 20 €/Mg
NF-Metals		*-570 €/Mg*
Fe-Metals		*-80 €/Mg*
RDF (only if costs landfill > RDF)		70 €/Mg
examples of landfill costs	**fees**	**taxes**
France	0 €/Mg	20 - 40 €/Mg
Greece	0 - 48,50 €/Mg	40 €/Mg
United Kingdom (UK)	4 - 29 €/Mg	3 - 97 €/Mg
Italy	1 - 10 €/Mg	79 - 94 €/Mg
Hungary	25 €/Mg	10 €/Mg

5. *Under which circumstances is the investment into the MARSS module worthwhile?*

Finally, to estimate the economic viability, the treatment and product costs as well as the revenues of the MARSS module were calculated and compared to the cost of exclusive landfilling of MBT outputs. Taking into account the assumptions made (e. g. mass balance, product prices, fuel vendees), the costs for a post-sorting of the dried MMSW in the MARSS module are lower than landfilling the waste as long as the landfill costs are above 45-60 Euros/Mg (for the first year of operation). Fig. 19 shows examples of the comparison between the post treatment of dried MMSW using the MARSS technology and the executive landfilling of the dried waste with the assumption that the landfill costs increase by 2 % each year. Apparently the MARSS module is only profitable in countries with significant landfill costs, such as Italy and the UK.

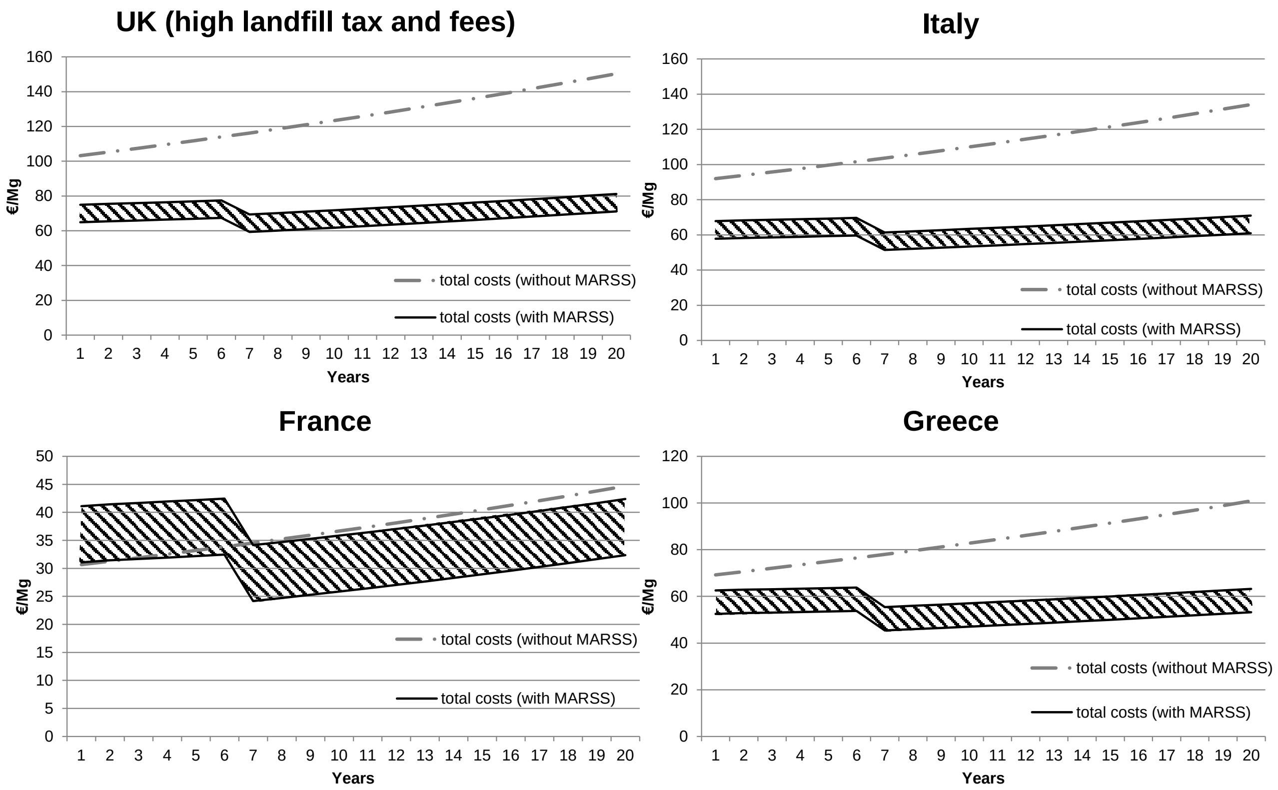


Fig. 19 Cost overview for landfilling and MARSS in different EU countries

5 ACKNOWLEDGEMENT

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