DELIVERABLE 3.1
TECHNICAL PLANNING AND ASSESSMENT OF MUNICIPAL SOLID WASTE MANAGEMENT SCENARIOS IN CASE STUDY REGIONS

Project:

“Waste management in transition economies”

WaTra

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Project Lead
University of Natural Resources and Life Sciences, Vienna – Institute of Waste Management (ABF-BOKU), Austria

Project Partners
Institute of Waste Management and Circular Economy – TU Dresden, Germany

Department of Urban Environmental Engineering & Management – National University of Urban Economy in Kharkiv, Ukraine

Department of Occupational Health and Safety –*Belarusian-Russian University, Belarus*

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TECHNICAL ASSESSMENT OF MUNICIPAL SOLID WASTE MANAGEMENT

Scenarios for the case study regions Mogilev (Belarus) and D. (Ukraine)

as part of the WaTra-Project

MASTER PROJECT THESIS

Laura Scharenberg

Technische Universität Dresden

Fakultät Umweltwissenschaften

Institut für Abfall- und Kreislaufwirtschaft

Dipl.-Ing. Roman Maletz

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CHP	Combined heat and power plant
$CO_{2,eq.}$	Carbon dioxide equivalent
DM	Dry matter
DOC	Dissolved organic carbon
FE	Ferrous
GCV	Gross calorific value
GHG	Greenhouse gas
HDPE	High-density polyethylene
kf – value	Permeability value
LCV	Lower calorific value
LOI	Loss of ignition
MBS	Mechanical-biological stabilization
MBT	Mechanical-biological treatment
MPS	Mechanical-physical stabilization
MSW	Municipal solid waste
NE-metal	Non ferrous metal
RDF	Refuse derived fuel
RTO	Regenerative Thermal Oxidation
TOC	Total organic carbon
VDM	Volatile dry matter
WaTra	Waste management in transition economies
WC	Water content
WMS	Waste management system

1 Abstract

Emissions and problems caused by waste are a global concern. Especially in transition economies and countries which are not highly developed the environmental issues have no priority. It is important to support these countries with experience in this field. In order to implement an organized waste management system, it is necessary to find simple but still efficient solutions.

In this thesis, we will describe different technical solutions for already developed scenarios for the two case study regions Mogilev in Belarus and D. in Ukraine. We will introduce different waste management facilities which are used for these scenarios: A sanitary landfill, one with and one without a landfill gas collection system, an MBT with a low level of technology and windrow rotting in the biological component and another MBT with optimized recovery rates of energy and material recovery. Furthermore, a composting plant, as well as the possibility of energy recovery through anaerobic digestion and a waste incineration plant, will be suggested.

On the basis of an unpublished Emission-Calculation-Tool from the Institute of Waste Management and Circular Economy (TU Dresden), we calculated the greenhouse gas emissions of the twelve different scenarios. The results showed that most emissions can be reduced with two methods: Either with the use of high technological processes and treatments or with an efficient selective waste collection system.

Moreover, it is obvious that every scenario and every waste management treatment considered in this thesis can reduce the emissions massively compared to the current situation.

Because of the small throughputs in the D. region, we would recommend to adapt the scenario with less technology and to introduce a high efficiency in the separate collection. Alternatively, a partnership with surrounding regions to increase the throughputs should be considered.

With the focus on emission reduction and energy recovery, all scenarios of the Mogilev region are feasible. The scenarios with the highest technical effort have the best net emissions. As there is already an existing sorting facility with a high capacity called ZUBR in Mogilev region, an upgrade to an MBT should be taken into closer consideration.

2 Introductory Chapter

This thesis is part of the project “Waste Management in Transition Economies” (WaTra). The first step of this international cooperative work was to collect data and compare the waste management systems in Western and Transition Economies (see Overview Report, WaTra 2017). One of the main aims of the WaTra-Project is to develop case studies for post-socialist economies. We chose to study and roadmap two regions, the D. region in Ukraine and the Mogilev region in Belarus, for our case studies. Both regions lack a waste management system equal to European standards.

The Austrian *University of Natural Resources and Life Sciences, Vienna – Institute of Waste Management (BOKU)*, developed in cooperation with the project partners waste management scenarios, which in the future, may be achievable in D. and Mogilev region.

In following sections, a short overview is given of the current situation in the two regions and the potential benefits of a well-organized waste management system (WMS). In subsequent sections, we will introduce the different scenarios in the case studies and explain the methodological approach of this thesis in more detail.

2.1 Status Quo

Although these two regions are in different geographical areas, have different political structures and are in different economical situations, their waste management systems are similar. To help understand their main problems, we summarized them as shown below:

- both regions lack full coverage of waste management services
- most of the collected waste is disposed on non-engineered landfills or on illegal dumpsites
- minimal amounts of separately collected recyclables
- convoluted organizational structures (overlapping control functions of different institutions)
- a lack of data collection
- activities in the informal sector
- limited official landfill capacities
- lack of proactive waste management solutions

For a more detailed report on each country and their waste management policies please refer to: “Overview Report of the Comparison of the Waste Management Systems in Western and Transition Economies” of the WaTra-Project.

Waste disposal in non-engineered landfills or dumpsites has negative impacts on the environment. Landfills without a low permeable bottom liner causes the leachate to percolate into soil and even into the groundwater. This leachate includes both organic and inorganic compounds, which can be toxic, carcinogenic, and ecologically damaging. Another problem is the production of methane (CH_4). The conversion of putrescible waste into methane in the absence of oxygen is a global concern. Methane is a greenhouse gas and is approximately twenty-one times more polluting than the same amount of carbon dioxide (CO_2). [Evans, 2001]

2.2 Methodological Approach

The decision of the optimal scenario to choose for each region will be discussed in a different section of the WaTra-Project. Among the many aspects to consider in the decision-making process we will only focus on the technical possibilities in this thesis.

The implementation of an efficient waste management system (WMS) can fulfill two different goals. The first is to protect the environment from negative issues. With a more organized waste management system and more developed waste treatment facilities, emissions can be reduced and negative environmental impacts can be prevented. The second goal is to produce a marketable product, which could be any kind of recyclable or production of energy. Ideally, the created product will be cheaper than the primary source.

History has shown that changes in waste management only happen when there are financial incentives or penalties. In order to analyze potential financial benefits, the following chapters will focus on the investment and operational costs of the different treatment plans as far as they are assessable.

The technical facts of the treatment facilities will initially be considered separately from the different scenarios and case study regions. We will then introduce the technical facts to provide an overview of the cost predictions and the potential emission reduction.

As a consequence of lacking existing data, the values for waste generation and mass input for the treatment facilities have been partly extrapolated and partly estimated. The values used are those that are expected as outcomes. We simplified the costs and quotes of the output streams by rounding to the nearest integer.

Since in every technical process the input material has an effect on the output material the composition of the waste needs to be defined. Data on the waste composition for each region exists but it includes a large unknown amount. Additional information on the waste composition is given in Chapter 3.1.

2.3 Description of Future Scenarios

As previously mentioned, the overview of the scenarios is simplified. The originally developed scenarios, which contain more accurate information, can be found in the master thesis of Monika Dobreva - *Ecological, Economical, Social & Technical assessment of municipal solid waste management system: a case study from Ukraine in D. region of N. province* and of Alena Sarokina - *Ecological, Economical, Social & Technical assessment of municipal solid waste management system: a case study from Belarus in Mogilev*. The focus of this project will be on the technical specifications of the treatment facilities, with an emphasis on the input and output streams of each step of the treatment process. Waste streams without obvious influences on the different treatments are left out of the figures. Other output streams, degradation losses, leachate, and evaporation etc. are also excluded.

All streams are stated in tonne per year. When the amount of the output streams is unknown, the flow charts are labeled with a capital.

On the basis of the flow charts below, we can easily figure out which processes need to be considered in detail.

2.3.1 Scenarios for the D. Region

While the status quo was discussed in Section 2.1, the following sections will illustrate the different scenarios. Figure 1 shows a simplified flow chart of the current situation in the D. region. Approximately 14,000 t are landfilled in non-engineered landfills each year, however, the collection of the waste is not completely organized. The current waste stream to the landfill includes bulky waste, WEEE (waste electrical and electronic equipment), and hazardous waste. In the scenarios these three streams will be collected separately, but will not be discussed further. There is a separate collection for recyclables, but the amount is insignificant (ca. 3 t/y).

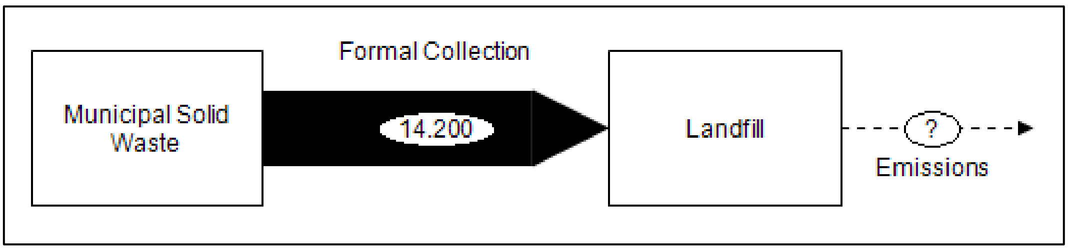


Figure 1: Current situation D. region (simplified)

Using the waste prognosis tool, according to *Boer at al 2005*, the waste amounts for the year 2025 were estimated by BOKU. The first step scenario (s. Figure 2) assumes that the ca. 15,100 t/y residuals will be treated with a MBT plant (bulky waste, WEEE, and hazardous waste excluded). After analyzing the different technologies, solutions for any unknown output streams will be discussed.

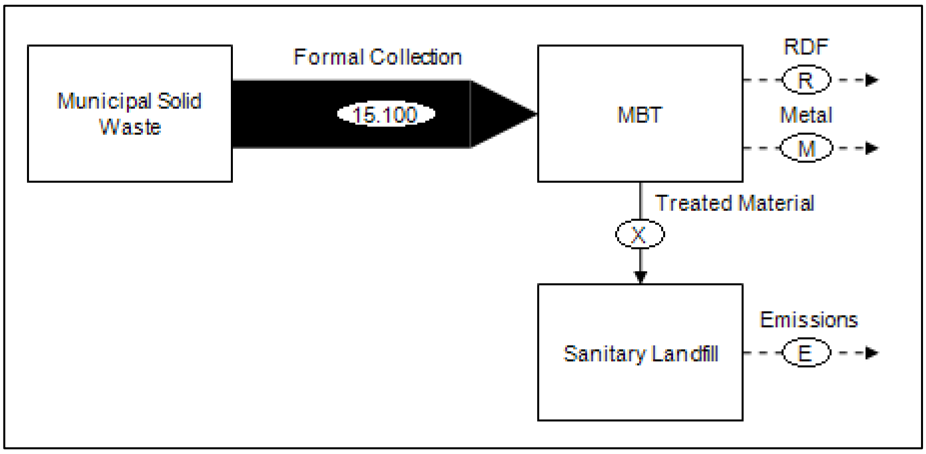


Figure 2: First Step Scenario - Sanitary Landfill + MBT

The scenarios for the D. region differ in the amounts of recyclables collected separately, which also leads to the differences in the amount of input into the MBT. Figure 3 illustrates Scenario 2B, in which a composting plant is added and Figure 4 shows Scenario 1B. The scenarios that are left out in this section can be found in the Annex-1.

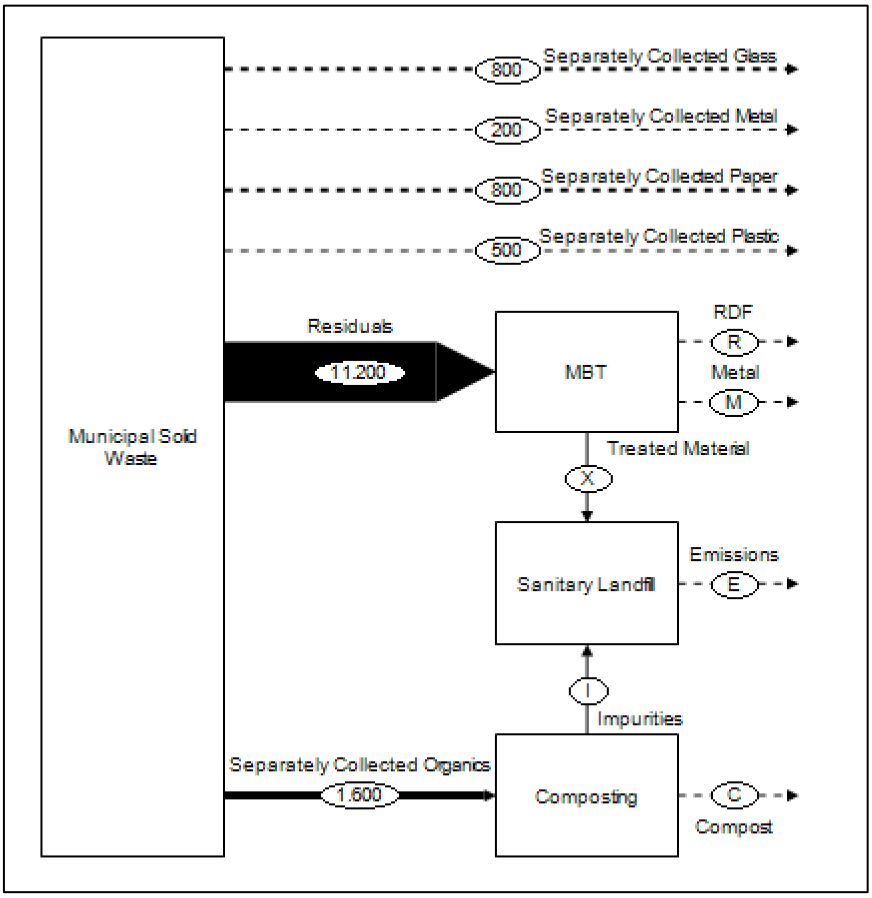


Figure 3: Scenario 2B - Full Recycling + Composting

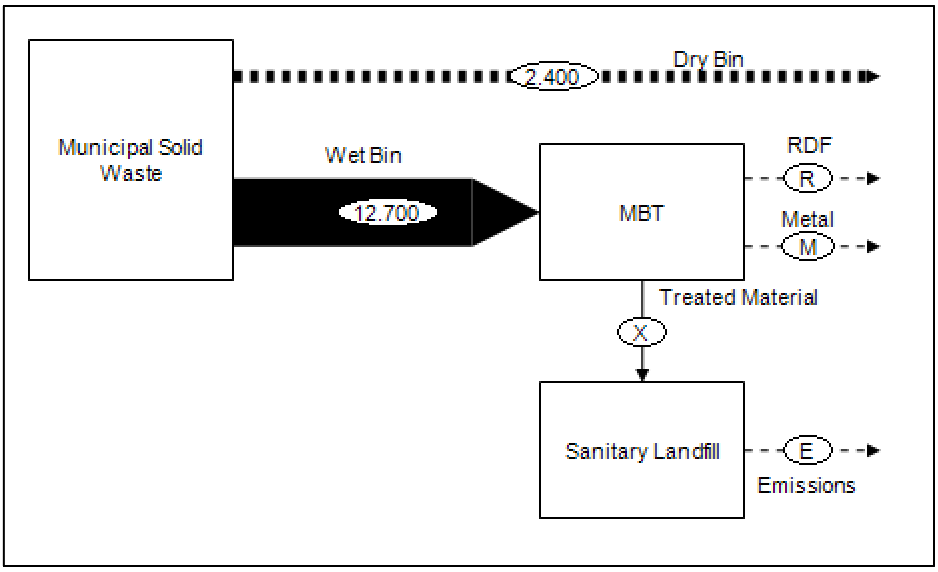


Figure 4: Scenario 1B - Partly Recycling

2.3.2 Scenarios for Mogilev region

A sorting facility already exists in the Mogilev region, which has a high capacity for manual sorting, called ZUBR. Figure 5 represents a simplified version of the current situation in the region of the case study. Approximately 80,000 t/y of residuals are sorted in ZUBR and ca. 110,000 t are landfilled, while ca. 7,000 t are collected separately each year.

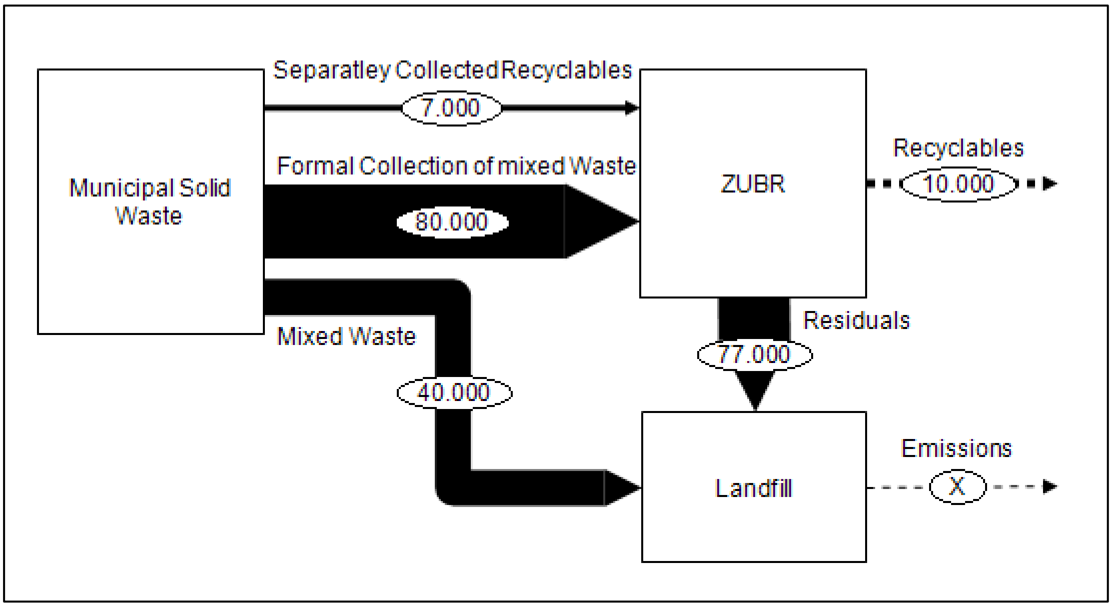


Figure 5: Current Situation Mogilev region (simplified)

The first step of the scenario includes ZUBR, but instead of sorting all the residuals, only the recyclables collected separately are sorted (s. Figure 6). According to the waste prognosis tool from *Boer et al 2005,* the total amount of residuals will be around 160,000 t/y by 2025. The bulky waste, WEEE, and hazardous waste will be collected separately as well, however, these streams will not be discussed further.

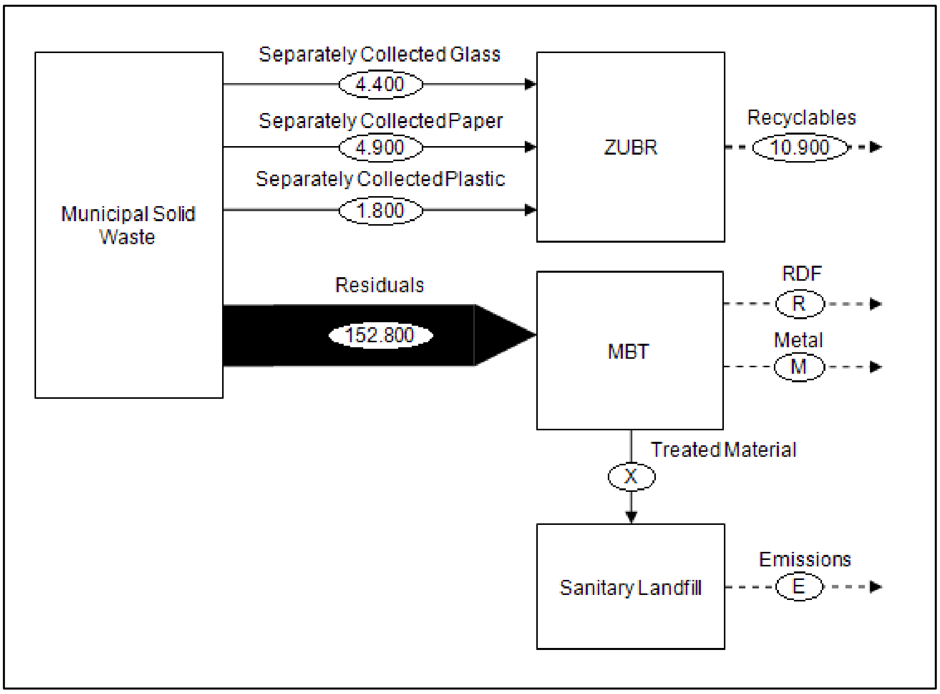


Figure 6: First Step Scenario Mogilev region

Four scenarios were developed for the Mogilev region. The first one is basically identical to the first step scenario, save for the amounts of recyclables collected separately. In the second scenario, the recycling rates are higher and a composting plant is added. In the third scenario instead of an MBT plant, an incineration is implemented. Finally, in the last scenario, the focus is on full energy recovery (Figure 7). Only metals and glass will be collected separately. The organic waste will be treated in an anaerobic digesting plant, and the resulting residuals get burned in the incineration plant. The other flow charts can be found in Annex-2.

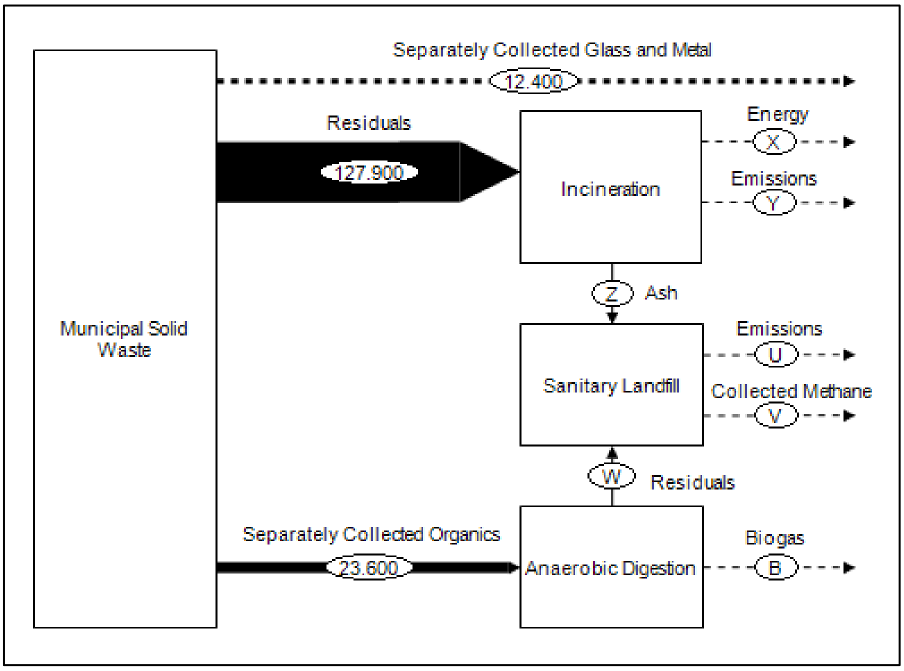


Figure 7: Scenario S4 - Full Energy Recovery

3 Facility Design

In this chapter, every technology used in the different scenarios is analyzed. As discussed in the previous section, the following treatment facilities have to be considered:

- Sanitary Landfill
- MBT
- Composting plant
- Anaerobic Digestion
- Incineration

There is not just one “low tech” or “high tech” version of each technology, but a multitude of possibilities. Discussing all possible scenarios is unrealistic, however, this project attempts to evaluate the most realistic scenarios, including the state of the art approach.

3.1 Waste Composition

The waste composition is an important factor for the waste management calculations. The composition differs from country to country, region to region and city to city. Variables influencing the calculations include building density, seasonal variations, population density, home composting, social structures, types of collection and so on. Additionally, newly implemented waste management systems, when developed, will generate different compositions than in the past.

It is often difficult to figure out the exact composition of the residuals, but increasing the number of manual sorting trials, conducted in different seasons and from different households, will help attain a more accurate average for a specific region.

While data about the compositions of the residuals from both case study regions are available, they do not exist in the fractional form needed for the calculations. These shortcomings impose use of available data and approximation of the unknown fractions from other averages (s. Table 1). On the positive side, information is available on the important compounds like the recyclables and organics.

Clearly, different outputs engender different inputs. It is therefore, imperative to realize that most of the results in this thesis are based on extrapolated compositions. That being said, the premises are reasonable and results can be accepted as realistic outcomes.

3.1.1 Waste Composition for the D. Region

The twelve different fractions were chosen according to an unpublished Emission-Calculation-Tool from the Institute of Waste Management and Circular Economy (TU Dresden). For the development of the scenarios and other calculations a prognosis tool according to *Boer et. al 2005* was used. The data on the organics, glass, metal, plastic, paper, wood and textiles is from the report of the case study on the D. region. The unknown amounts of minerals, composites, fine fraction, pollutants and “others” were divided from the other fractions after the averages from different literature sources and residual-sorting-trials were calculated [Kern 2006, Bilitewski 2013, Hoeß 2012].

The “others” fraction is generally slightly lower than the 30 Mass-%. Table 1 illustrates the progression of creating the waste composition and Figure 8 shows this composition in a pie chart.

Table 1: Progress of creating Waste Composition for D. region

Waste Composition needed for CO2-Tool	Waste Composition used Prognosis Tool	Report D.region	Average Different Sources	Assumed Waste Composition
organics	20 mass-%			20 mass-%
glass	7.5 mass-%			7.5 mass-%
FE/NE metals	1.7 mass-%			1.7 mass-%
plastic	4.5 mass-%			4.5 mass-%
paper/cardboard	7 mass-%			7 mass-%
wood	-	2 mass-%		2 mass-%
textiles	-	2-5 mass-%	4	4 mass-%
minerals	-	-	8	8 mass-%
composites	-	-	5	5 mass-%
others	-	-		29.9 mass-%
fine fraction	-	-	10	10 mass-%
pollutants	0.4 mass-%			0.4 mass-%
total	41.1 mass-%	2 mass-%	27 mass-%	100 mass-%
unknown amount	58.9 mass-%	39.1mass-%	29.9 mass-%	

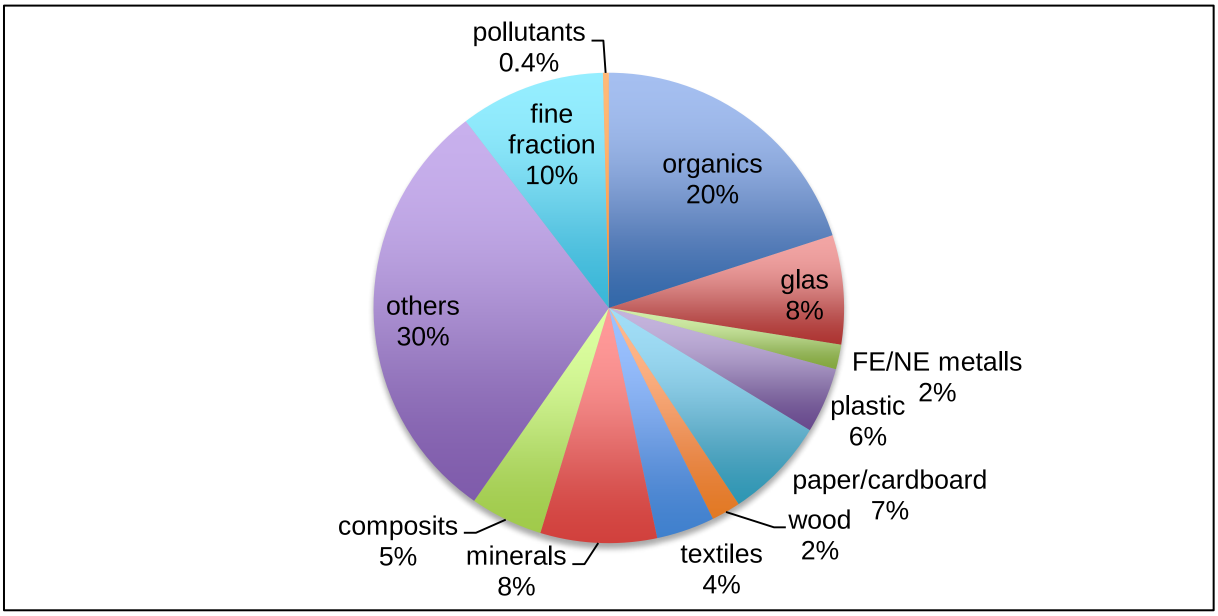


Figure 8: Assumed Waste Composition for D. region in [mass-%]

3.1.2 Waste Composition for Mogilev region

The same process for estimating the waste composition in the D. region was used for the estimations in the Mogilev region. Table 2 illustrates the progression of creating the waste composition and Figure 9 shows this composition in a pie chart. The "others" fraction with 18 mass-% is lower than in the composition of D. region, but is still higher than it normally would be.

Table 2: Progress of creating Waste Composition for Mogilev region

Waste Composition needed for CO2-Tool	Waste Composition used Prognosis Tool	Report Mogilev	Average Different Sources	Assumed Waste Composition
organics	30 mass-%			30 mass-%
glas	7 mass-%			7 mass-%
FE/NE metalls	2 mass-%			2 mass-%
plastic	3 mass-%			3 mass-%
paper/cardboard	8 mass-%			8 mass-%
wood	-	5 mass-%		5 mass-%
textiles	-	3 mass-%		3 mass-%
minerals	-	-	8 mass-%	8 mass-%
composites	-	-	5 mass-%	5 mass-%
others	-	-		18 mass-%
fine fraction	-	-	10 mass-%	10 mass-%
pollutants	1 mass-%			1 mass-%
total	51 mass-%	8 mass-%	23 mass-%	100 mass-%
unknown amount	49 mass-%	43 mass-%	18 mass-%	

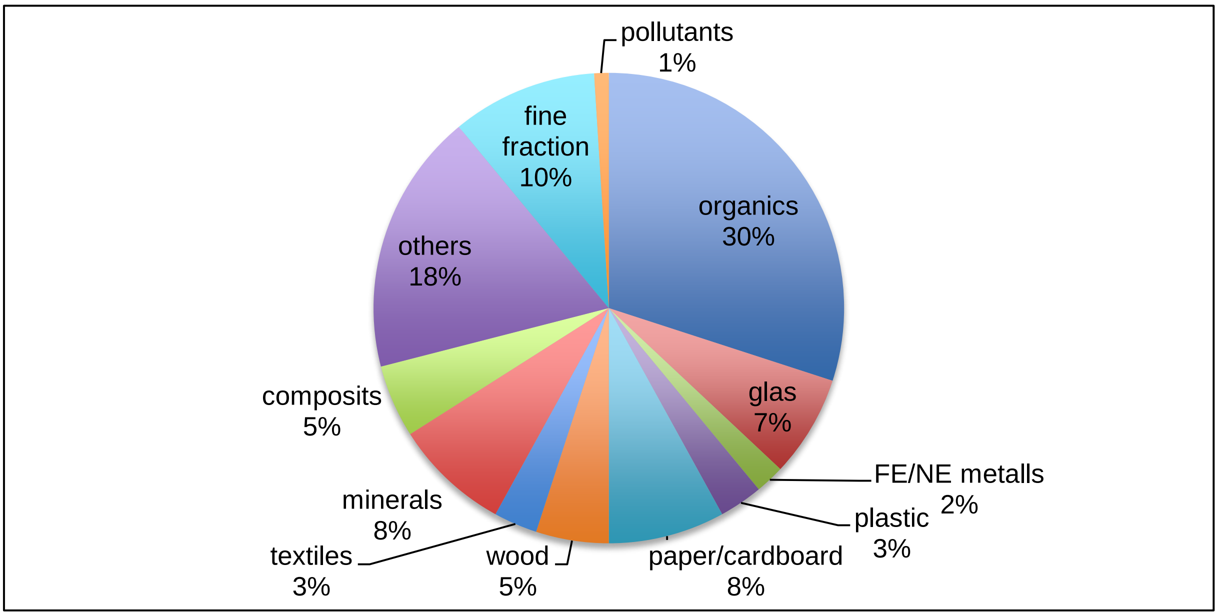


Figure 9: Assumed Waste Composition for Mogilev region in [mass-%]

3.2 Sanitary Landfill

The objectives of sanitary landfills are to improve waste management by:

- Reducing/preventing negative impacts of waste to the environment
- Volume reduction
- Improve assembling residuals
- Arrangements for inspection
- Post-use care

Both case study regions include a sanitary landfill in the “first-step-scenario.” One possibility to set up a sanitary landfill is to upgrade an already existing landfill with engineered technology. Alternatively, a new landfill could be built elsewhere. The landfills, which are in use at the moment in both regions, only have an infilling capacity for the next few years. Therefore, building new landfills should be considered for future scenarios. Nevertheless, to avoid greenhouse gasses from being released, due to biological activity, which can continue on for years after waste infillings have stopped, it also makes sense to upgrade the old landfills.

A project for upgrading the landfills in the D. region already exists. In that project they want to install systems of collection and utilization of landfill gas to generate electricity, funded by the World Bank [WaTra – Report about Case Study Region D. 2017]. Because the WaTra project is not connected to the landfill project, the effects it will have on the WMS is unknown, and was therefore omitted from the following considerations.

The European Union landfill operation is regulated by the directive 1999/31/EC, and is part of national law in Germany under the Landfill Ordinance (DepV). One of the directive’s main elements is that it defines the landfill classes, which are:

- landfill class 0, DK 0: Overground landfill site for inert wastes
- landfill class I, DK I: Overground landfill site for wastes with low organic content
- landfill class II, DK II: Overground landfill site for MSW (pretreated)
- landfill class III, DK III: Overground landfill site for hazardous wastes
- landfill class IV, DK IV: Underground landfill site

In order to minimize negative effects of landfilling on the environment and human health, engineered landfills use a so-called multi-barrier concept. The concept is a combination of several independent safety measures, which ensure the protection of the environment even if one of the barriers fails. [LUBW 2017]

The barriers are hierarchically structured:

1. Pretreatment of the waste
2. Site selection (suitable geological and hydrological conditions)
3. Configuration of landfill body (structural stability)
4. Base lining system (and leachate treatment)
5. Surface cover (gas collection)
6. Landfill operation and post-use care

[LUBW 2017]

The Landfill Ordinance also defines minimum requirements for the six barriers for each classification. The allocation criteria, which are needed to satisfy the landfill class II criteria, is described in the Annex 3 – Table 2 of the Landfill Ordinance. The limiting values for the loss of ignition is LOI ≤ 5 mass-% and TOC ≤ 3 mass-% for organic carbon. These limiting values shall not be permissible for mechanically and biologically treated wastes. For MBT treated waste, the following provisos will apply:

- The requirements with regard to the organic component of the dry residue of the original substance shall be deemed satisfactory if TOC does not exceed 18 mass-% or the gross calorific value (GCV) does not exceed 6,000 kJ/kg
- The max. DOC shall be 300 mg/l
- The biological degradability of the dry residue of the original substance shall not exceed 5 mg/g (determined as AT_4 respirometric activity) or 20 l/kg (determined as the gas formation rate in a GB_{21} fermentation test).

[DepV 2009]

Because every scenario is pretreated in a MBT or incineration, it is assumed that the wastes, which will be landfilled, satisfy the previous listed values. The essentials components of a sanitary landfill are already summarized in the six points of the multi-barrier concept. Figure 10 also gives an overview of the basic technologies of a sanitary landfill.

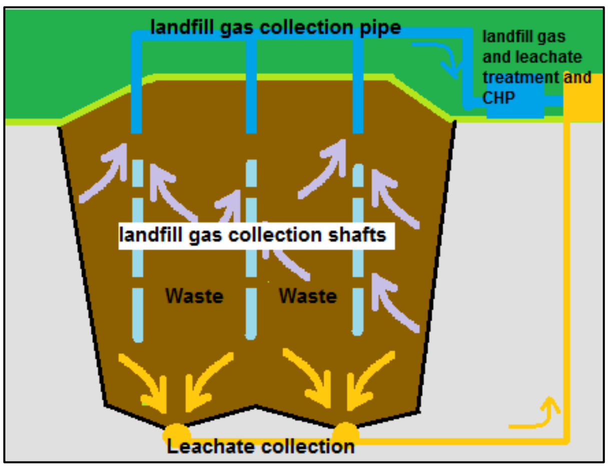


Figure 10: Basic Components of Sanitary Landfill Class II [after UBA 2014]

Selecting a site for the landfill is a key step in the facility design. Clearly, the most important aspect in determining the total capacity size, is estimating how much waste will be landfilled each year. Sanitary landfills should be designed to hold a minimum of 10 years capacity, but ideally for 15 – 20 years. This extended time would allow amortizing the investment, construction, and closure costs. Apart from the special requirements, the landfills have to meet several location and geological criteria:

- Sufficient distance from groundwater level
- Low permeability value of the soil (kf-value ≤ $1 * 10^{-6}$ m/s) [DepV 2009]
- Sufficient distance from: residential areas, lakes, rivers, critical habitat area, water supply wells, airports etc.
- Adequate infrastructure

The landfill ordinance characterizes the subsoil as the geological barrier. The subsoil of the landfill site and the substrate in the wider surrounding area should be able to substantially obstruct any pollutant from dispersing from the landfill. Consequently, the subsoil needs to be investigated in terms of permeability, thickness and homogeneity, as well as, its capacity to retain pollutants.

Waste may only be accepted if it fulfills the acceptance criteria. It is therefore, important to have an unloading area where the delivered waste gets a first visual inspection and a laboratory where sample investigations are made. It is also necessary to weigh the delivered waste with a truck scale and record the data.

A combined base lining system is shown in Figure 11.

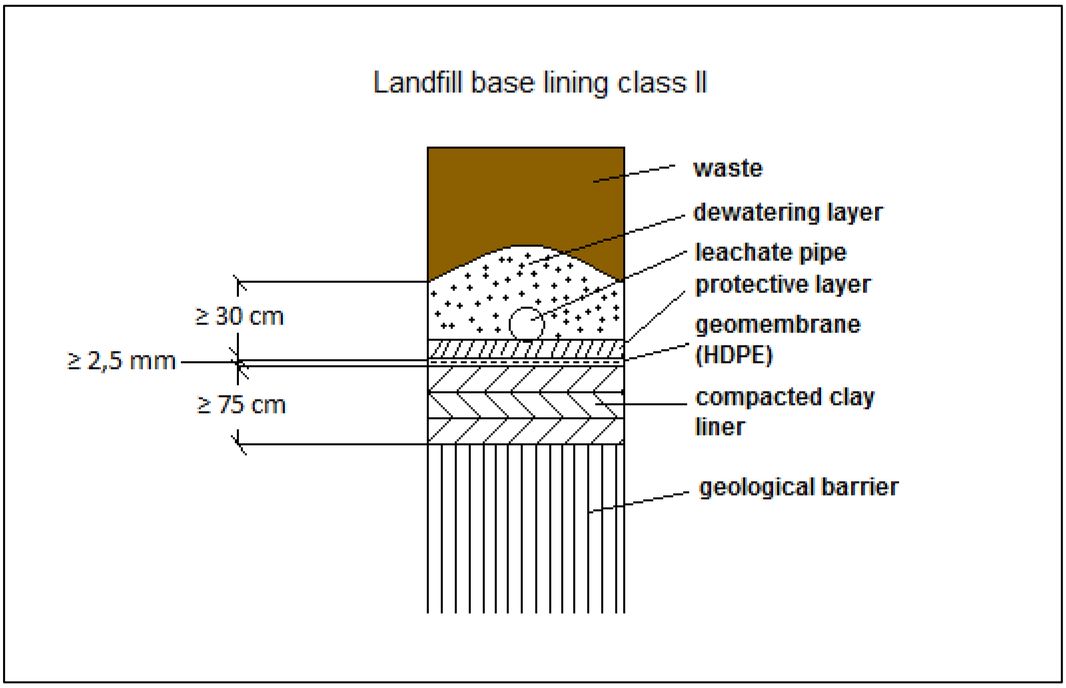


Figure 11: Construction of a combined base lining system [after TASi 1999]

The base lining system starts with three liners of compacted clay, which need to be a minimum of 0.75 m in height. The clay is topped with a flexible geomembrane (preferred material: HDPE), and should have a minimum thickness of 2.5 mm and a kf – value of ≤ 5 * 10^{-10} m/s. This membrane needs to be covered with a protective layer of fine sand or similar material. On top of the protective layer is a dewatering layer, or drainage layer, which is made of chippings or gravel with a kf – value of ≤ 1 * 10^{-3} m/s. In this layer, the drainage pipeline is installed to collect the leachate. [TASi 1999, DepV 2009]

The leachate needs to be treated in a leachate treatment facility on site or collected and disposed in another wastewater treatment facility.

The construction of a surface sealing system is shown in Figure 12. On sanitary landfills, the landfilled waste is compacted into layers every evening of a working day and is subsequently covered with clay. If one part of the landfill reaches the maximum height capacity, the surface needs to be covered in the following method:

- a leveling layer
- a gas drainage layer made of gravel or similar material
- 0.5 m thick mineral liner with kf – value of ≤ 5 * 10^{-9} m/s
- geomembrane minimum thickness 2.5 mm
- 0.3 m thick dewatering layer with kf – value of ≤ 1 * 10^{-3} m/s
- a one meter high recultivation layer (soil material)

[TASi 1999, DepV 2009]

The quality and quantity of the landfill gas vary with time, but it needs to be collected, treated and can then be transformed in a CHP to electricity and heat. The gas can be used for the landfills own energy requirements or it can be fed into the grid.

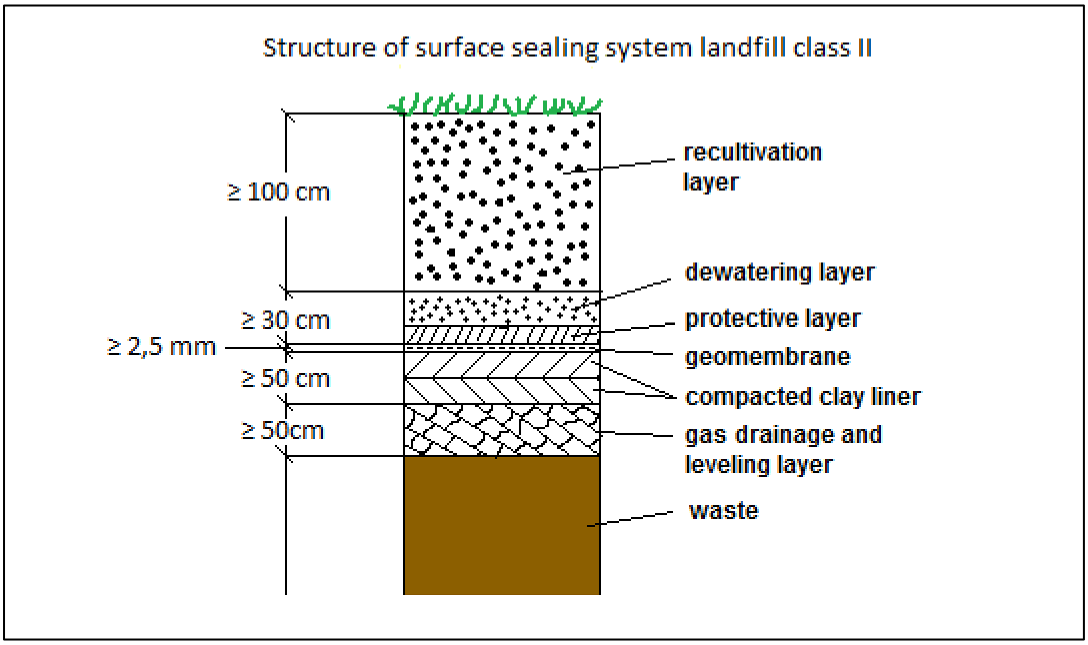


Figure 12: Construction of a Surface Sealing System [after TASi 1999]

Monitoring and auditing are a part of the landfill operations. After a landfill is closed it needs to be monitored for approximately 30 more years. Monitoring includes measuring the leachate and gas emissions or the settlement of the waste and soil.

3.3 Mechanical Biological Treatment

Mechanical Biological Treatment (MBT) is a generic term for a number of waste management processes, such as material recovery facilities, refuse derived fuel (RDF) production, mechanical separation, sorting, composting, and stabilization; MBT plants are designed primarily to process residuals. During mechanical separation, the valuable recyclables and RDF can be separated. During the biological process the residuals can be pasteurized through composting or anaerobic digestion. One main advantage of the MBT technology is the flexibility of the design and construction, which can be adapted to the legal and technical circumstances for each site. Depending on the different compositions of waste and the different contents that can be recovered, different types of treatment can be chosen.
Thus, MBT can be divided into three technology options:

- Mechanical-biological waste treatment (MBT)
- Mechanical-biological stabilization (MBS) or biological drying
- Mechanical-physical stabilization (MPS)

The aim of the MPS is to produce RDF using mechanical and physical processes. Often, the physical drying process needs a large amount of energy and is not economical, and will therefore not be discussed in more detail.

The biological treatment of the MBT can be distinguished into the following systems:

- Aerobic stabilization (rotting)
- Anaerobic digestion

All types of biological treatment use a mechanical front processing technique for the waste. The most modern facilities use a front-end mechanical processing to optimize the recovery of recyclables and RDF production. This technique typically combines individual system components:

- Impurities, which could disturb the process (bulky waste, mineral fraction)
- Recyclables (Fe-metal/NE-metal)
- High caloric fraction, which can be used as RDF (plastic, composites, paper and cardboard, textiles, wood)

With a wide range of variations of those components:

- Comminution
- Sorting units

- Sieving units
- Separator after density (ballistic separator, air separator etc.)
- Metal separator (magnetic separator, eddy-current separator etc.)
- Mixer/homogenizer

In Figure 13, two MBT flow charts are shown: one with composting/rotting and one MBT with anaerobic digestion. As shown in the mass flow, the mechanical processing steps can separate products in a fairly wide range. This is due to the many different units and technologies that can be used.

The main target of the aerobic stabilization (MBT with intensive rotting and post-rotting) is to stabilize the waste by reducing the biodegradables content in the municipal waste. This reduces the amount of waste going to the landfills and adheres to the requirements of the EU landfill directive. Additionally, MBT with anaerobic digestion produces biogas that can be used to satisfy internal electrical power generation and heating requirements.

In the MBS, the processing order is switched, the whole input mass is stabilized first, which leads to a better mechanical separation and reduces the amount of waste going to the landfill.

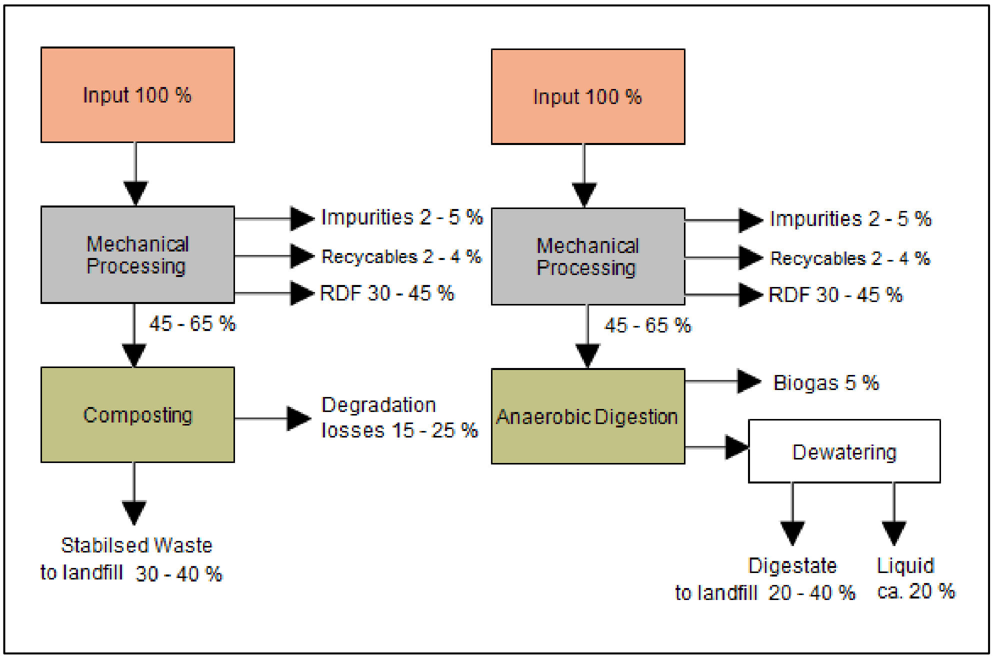


Figure 13: MBT output streams [after Bonnet 2007, Bockreis 2011, UBA 2014]

The minimal technical equipment needed for the mechanical component is:

- Storage facility and charging devices
- Separation of impurities
- Comminution

Most MBT plants use a delivery hall (flat bunker) as a storage facility. Bulky impurities can be removed easily with a wheel loader, and at the same time the waste can be overviewed and checked the quality. In a delivery hall, different types of waste such as MSW, bulky waste, and industrial waste can be stored. Because these processes are done above ground, delivery halls have a greater space requirement than an underground bunker.

The biggest difference in the mechanical aspect of the various facilities is the process of material comminutioning. The comminution units are more expensive than other units in MBTs, which have high tribological behavior and require large amounts of energy. While the monetary investment is high, they will have a big impact on the efficiency of the mechanical and the biological component of the MBT. The reaction surface made from comminution increases and materials that are packaged can be made available.
Due to the higher costs, not every MBT uses comminution units, but if bulky waste is to be processed in the plant, it will always need some sort of shredding process.

- Rough comminution: 250 – 500 mm
  rotary shears, shredders, crushers
- Main comminution: 100 – 250 mm
  rotary shears, shredders, grinders
- Fine comminution: < 25 mm
  hammer mill

[UBA 2014]

The Fe-metals can be separated easily with an overbelt magnetic separator. The only precondition for high recovery rates is an adequate allocation of the material on the assembly line. Most of the MBT have such a unit.

The non-ferrous metals can be separated with an Eddy-current Separator. If it is included in an MBT, the Eddy-current Separator is usually inserted in the material stream < 80 mm.

A very important unit is the trommel sieve. It is a heavy duty robust building unit, with low maintenance and is available with different technical features, such as, trommel throughput, hole width -with more than two output streams (fine, middle, large), and many more. Nearly every MBT has at least one trommel sieve in the processing line.

3.3.1“Low Tech” MBT

With those units, the “low tech” mechanical part of an MBT plant can be designed. One possible design could match the flow chart in Figure 14. All the minimum technical requirements are included. The comminution unit will shred the material into 100 -250 mm pieces. The trommel sieves material < 80 mm goes straight to the biological treatment. The fraction > 80 mm is thinned out with different speeds of assembly lines, so that the magnetic separator can collect the Fe-metals. Afterwards, the remaining impurities will be manual sorted out and the RDF fraction remains as the final output stream. Manual sorting wet residuals is not advisable for health reasons.

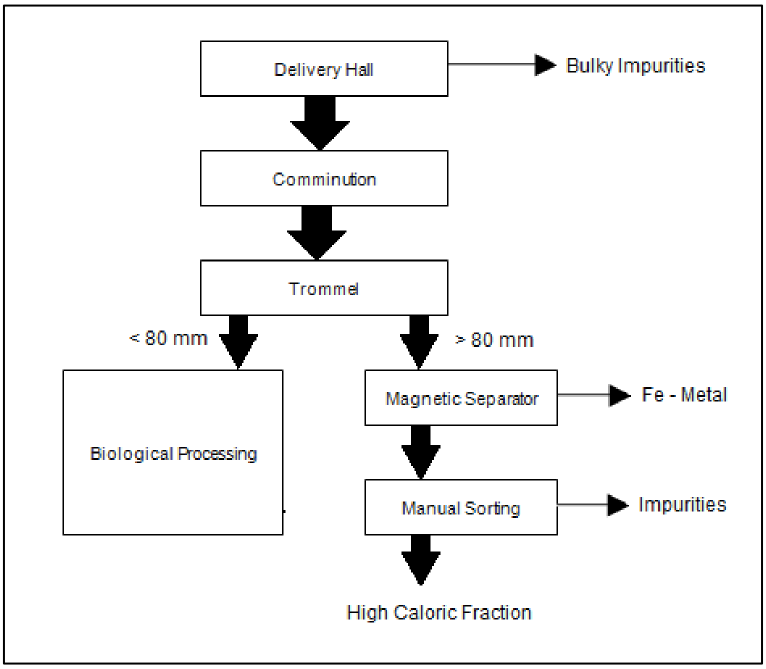


Figure 14: Flow Chart mechanical processing MBT "low tech"

Facilities with a high yearly input usually have automatic sorting units like NIR-scanners, ballistic separators or air separators. But this “low tech” version could be a possible option for both case study regions, since ZUBR in the Mogilev region is a manual sorting facility for wet residuals with high capacity and the yearly input amount in D. region is not too high.

For the biological processing, only basic technological equipment is needed to achieve windrow rotting. To ensure the groundwater does not get contaminated, only a non-permeable underground is needed. However, static windrows, with no technical based aeration and watering system, can only be used for post-rotting. The cheapest and most basic technology for the intensive rotting system is the “Chimney Process” after Spillmann/Collins (Figure 15). It uses a self-aeration windrow technology, in which flexible and perforated drainage pipes are installed crosswise under the windrow. The distance between each pipe is 3 – 4 m and in the middle of the windrow, these pipes are led out like chimnies. Because the rotting material self-heats, an airflow is created to ensure the aeration of the windrow. Additionally, the water content is kept constant through precipitation. The windrow can be 2.5 m high and 30 m wide, and after 3 – 6 month the windrow needs to be turned mechanically. On top, the windrow is covered with compost that should reduce the odor and pollution emissions. [Bilitewski 2013]

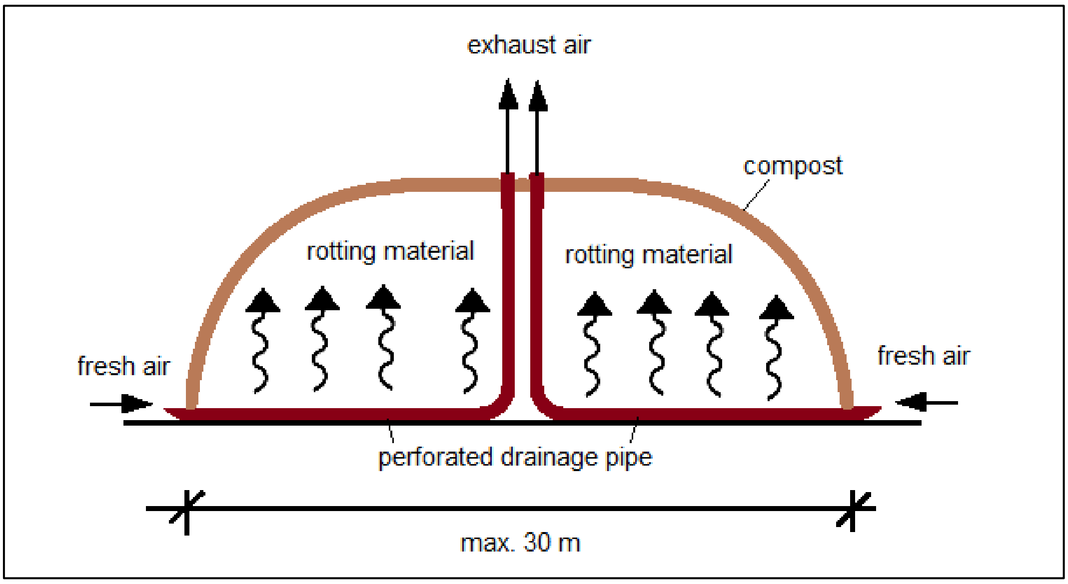


Figure 15: Schema of the "Chimney process" after Spillmann/Collins [figure after Bilitewski 2013]

There are many other technological options for biological processing, theoretically every composting or anaerobe digestion can be used. For more information please see Sections 3.4 and 3.5.

3.3.2 “High Tech” MBT

The MBT concept should be clear by now, however, due to the many variations to this process, it is not practical to name one optimal “high tech” MBT process. Most of the units that can be used have been discussed, but many more constellations are conceivable. Ultimately, it is a question of quality, reliability, and economical value. Before presenting the “high tech” facility we chose, here are some general facts about MBTs in Germany:

- 61 mechanical treatment plants and 38 of them are MBT [Thiel 2011]
- The average input into German MBT plants is about 100,000 t/y [UBA 2014]
- Most of the MBT are aerobic plants, but the trend is moving to a combination of aerobic and anaerobic treatment [IFAS 2012]

It is not clear what amount of minimum throughput is needed for MBTs to make it economically attractive. When considering the economical factors, it is important to keep in mind, that in Germany, plant operators have to pay to give the RDF to a co-incineration plant and we assumed, that the RDF will bring revenues in Ukraine and Belarus.

<u>Throughput</u>

The design data for MBT was calculated with the following assumptions:

- 250 d/y, 16 h/d, plant availability 85 % → 3,400 h/a [Sabery 2003]

Yearly input in the Mogilev region for the different scenarios varies from 112,000 t/y in the full recycling and composting scenario, to 152,000 t/y in the first step scenario, which corresponds to a throughput of 32 t/h to 45 t/h (difference 13 t/h).

Yearly input in the D. Region for the different scenarios varies from 11,200 t/y in the full recycling scenario, to 15,100 t/y in the first step scenario, which corresponds to a throughput from 3.29 t/h and 4.44 t/h (difference about 1 t/h).

The costs for technological units decrease when throughput increases. However, this cannot be generalized and it is important to keep in mind, that the throughput amount is an important factor for the choice of which technology to use.

It can be assumed, that the "high tech" version is not suitable for the D. region, because of the low throughput. To increase throughput, a partnership with surrounding regions/cities or acquiring suitable waste from the industrial sector should be considered.

One of the biggest MBT's in Germany is the MBA Cröbern with a capacity of 300,000 t/y (bulky waste included). The mechanical treatment includes different comminution units, sieves, air classifiers, Fe-separators, Eddy-current separators, and NIR-sorting. The mechanical treatment is followed by an aerobic biological treatment, which entails a 5-week intensive rotting in rotting tunnels, and a 10-week post-composting in windrows. A flowchart and further information can be found in *Christensen 2011 – Solid Waste Technology and Management* or on the ZAW - Zweckverband Abfallwirtschaft Westsachsen website: *www.zaw-sachsen.de*

Another MBT worth mentioning is the MBA Kahlenberg. It uses newer technology compared to a conventional MBT. Essentially, it is a combination of a mechanical pre-treatment, an aerobic and an anaerobic combined process, and a mechanical post-treatment. It has several advantages, such as:

- it has better quality of the RDF
- it minimizes the residuals to landfill
- it produces enough biogas for the energy requirements for the whole facility

The facility design is shown in Figure 16 and was made in according to *Rettenberger 2005, Merten et al 2006* and *Person 2012*.

Bulky impurities and obvious pollutants are sorted out in the delivery hall by wheel loaders, and the residuals are fed in the process. After the mechanical pre-treatment, the waste goes into six big waste mixers. 1 m^3 water is needed per tonne of waste. This mixture is left for 3 days, in order for the organic compounds to dissolve in the water. Afterwards, the "waste pulp" is processed with a press, and subsequently, the pressed water is filtered and run through digesters. The dry matter goes straight into the biological drying tunnel, and stays in it for about 10 days. It follows a second mechanical treatment.

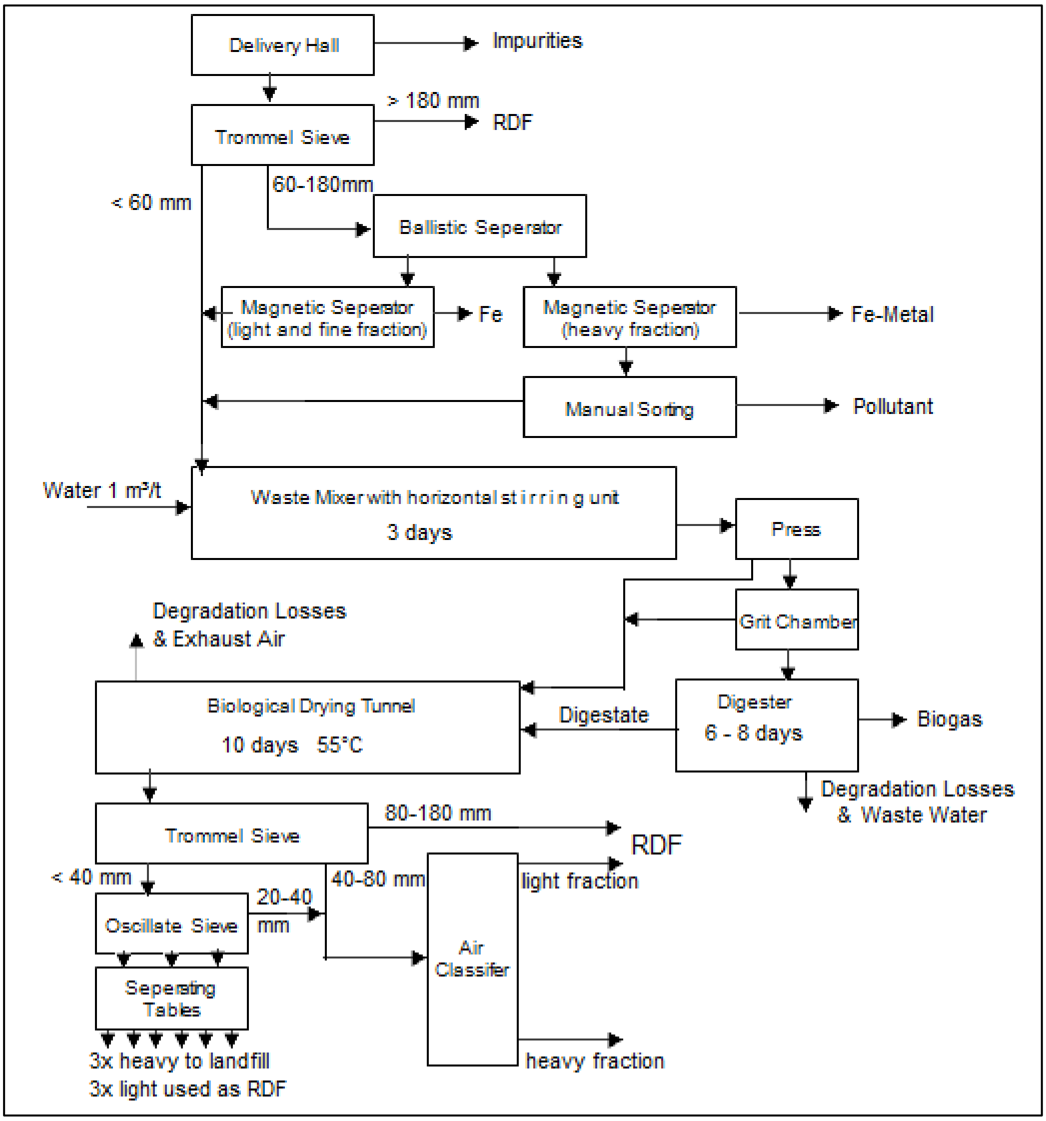


Figure 16: MBT Kahlenberg – Simplified Flow Chart

Final output streams are:

- RDF: 30 – 38 %
- Biogas: 5 – 8 %
- Metal: 1 – 2 %
- Residuals: 2 – 6 %
- Inert Material: 10 – 11 %
- Waste Water: 19 – 23 %
- Degradation losses: 18 – 29 %

[Rettenberger 2005, Mertens et al 2006, Person 2012]

The processed water and sludge is partly guided in a cycle, creating polluted air. The air that is slightly polluted from the delivery hall is treated with a biological filter and the heavily polluted air from the drying tunnel is treated in an exhaust air scrubber followed by an RTO. These units and the CHP are left out in the previews flow chart.

High tech facilities like the MBT Kahlenberg have advantages and disadvantages, but they clearly optimize recycling and energy recovery.

With 47 Mio € investment costs [Mertens et al 2006], this MBT is more expensive compared to other options (s. Section 4.2 – MTB costs), but operational costs decreases because this MBT needs less auxiliary fuels due to biogas production. Furthermore, collecting organics separately is not necessary because this process is designed for residuals including organics. Landfill costs and relating emissions can be saved as well.

3.4 Composting

Composting is the exothermic decomposition of biodegradable materials in the presence of oxygen. Composting is a process by which organic wastes are broken down into simpler forms by microorganisms - generally bacteria or fungi. In the context of this thesis, it is always implied that organic waste is waste from the kitchen and garden. This organic waste is mainly composed of carbon and hydrogen elements that are used by microorganisms as an energy source. Apart from avoiding emission of methane, composting has the significant benefit of producing high quality compost to enhance soil quality. Another advantage of composting is the reduction of the waste volume. During the composting process, the intense microbial activity causes the material to heats itself, thereby killing many unwanted organisms, such as weed seeds and pathogens. [Thomé-Kozmiensky 1995]

Organic waste has a high level of water content and a low heating value. The technology used in the process does not actually differ much from that used in the MBT. The microbiological and biochemical procedures are identical, the only difference between the two, is the input material of either the residual mixed waste or the organic waste. [Thomé-Kozmiensky 1995]

The microbial degradation process of the organics is a part of the natural material cycle. Dealing with large quantities of organic waste requires a much larger scale of operations, particularly in handling material, residence time, and oxygenation of the decomposing matrix. [Evans 2001]

The principle of providing large-scale controlled conditions to manage the production of a safe and stable end-product is well established. After considering the composting process itself, examples will be given of composting facilities.

The composting process can be divided into three phases as demonstrated in Figure 17.

1. Mesophilic phase (Ambient temperature – c. 40°C):
   After acclimation, infiltration and colonization of the material by the bacteria, fungi and other micro-organisms responsible for composting, the micro-organisms start growing and reproducing. This leads to higher respiration rates and an increase in temperature.
2. Thermophilic phase (c. 40°C – c. 60°C):
   During this phase the highest temperature is reached, and maximum pathogen sterilization takes place. At the end of this phase, temperature drops to around 40°C.
3. Maturation phase (c. 40°C – ambient temperature):
   The maturation phase is a slow, secondary mesophilic phase. Subsequently, as biological activity within the material decreases, temperature drops to ambient level. Complex structures like lignin are transformed into humic compounds and residual ammonia undergoes nitrification to nitrite and ultimately to nitrate. [Evans 2001]

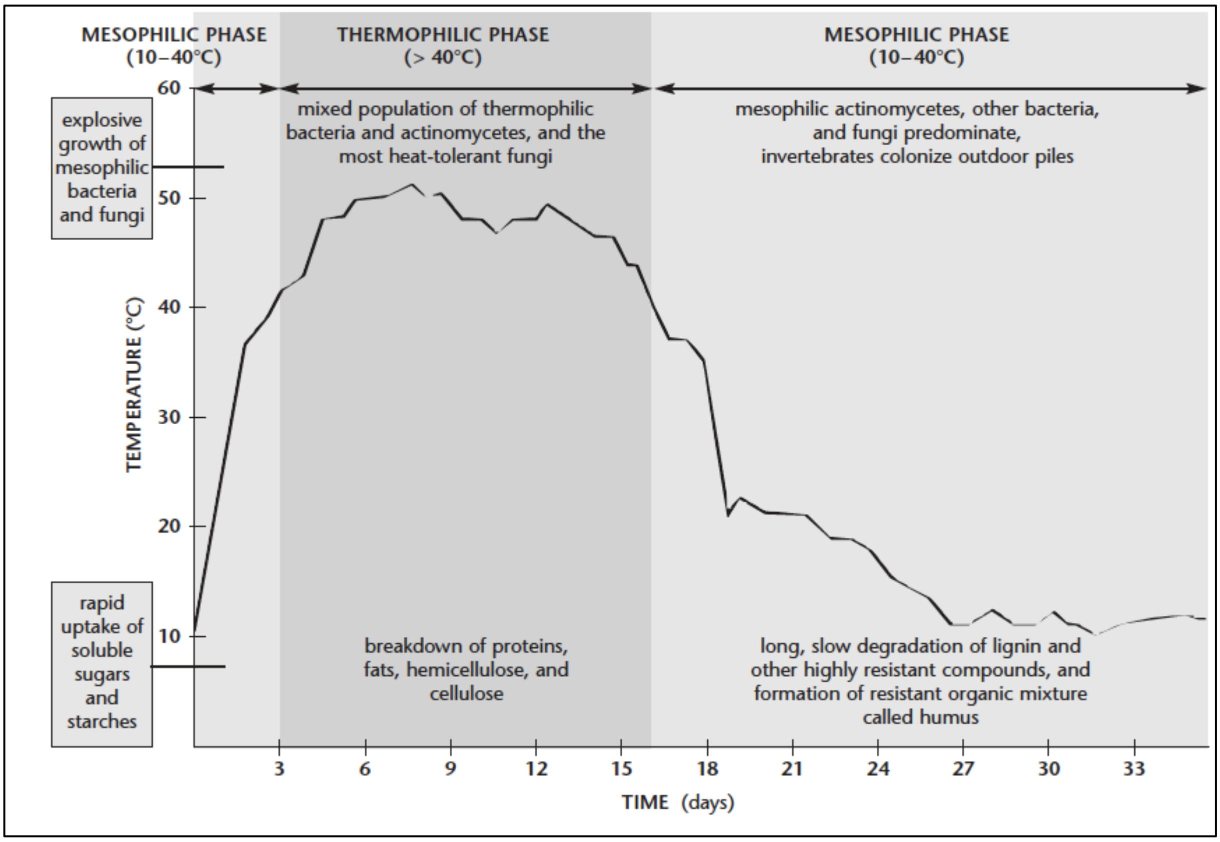


Figure 17: Temperature and phases of composting [Trautmann 1997]

Even though the exact details of processing depend on specific techniques, equipment, and management of the composting system, the efficiency of the degradation of the material and the quality of the end product depend on several general parameters. These operational parameters are shown in Table 3.

Table 3: Operational parameters of composting [after Dornack 2016]

Parameter		Remark
C/N ratio	≈ 20 - 25	Optimal bacteria growth
pH	≈ 7 - 9	
Water content	≈ 45 % - 65 %	Nutrition supply
Temperature	≈ 25°C … 55°C	Depends on phase
Air pore volume	≈ 25 % - 50 %	Oxygen supply
Size of pieces	≤ 1 cm	Wood
	2 – 5 cm	Kitchen waste

Virtually every composting plant is equipped with a variation of the following processing units:

- Pre-treatment (mechanical or manual sorting, shredding, homogenizing)
- Intensive rotting
- Post rotting
- Compost processing (sieving, separate impurities)
- Air and wastewater treatment

The better the pre-treatment, the better the compost quality. Separating impurities such as stones, glass, metals or plastic bags with a trommel sieve, a magnetic separator, or a manual sorting procedure, will make the rotting process even more efficient. Shredding the materials provides more surface area for the bacteria to grow on, while simultaneously homogenizing the mass. During the pre-treatment, the operation parameters can be justified with add-ons, such as water or structure materials.

Rotting is the main part of the composting process. It can be divided into different steps, but the terms of these steps are not consistently defined in literature and in this thesis, the terms intensive rotting and post rotting are used. During intensive rotting, pathogen sterilization takes place. The easily degradable substances are degraded and fresh compost is produced. During Post-rotting, the fresh compost becomes the end product, or “finished compost”, in which all the poorly degradable substances, such as lignin, are degraded. [Thomé-Kozmienski 1995]

It is critical to have adequate oxygenation of the composting material, because proper aerobic breakdown of the organics can only take place if the microorganisms responsible are provided with a sufficient supply of oxygen. Composting plants typically have mechanical turning systems, or pump air directly through the matrix to prevent anaerobic areas within the material composting.

Rotting systems can be distinguished between static, quasi-static or dynamic systems. Most established static systems use windrow composting. Windrow composting can also be used in the post rotting segment of intensive rotting, but in order to guarantee the stabilization of the dry matter, very long retention times (up to 60 weeks) are needed. Mechanical turning shortens this process. [UBA 2014]

Other categories of composting systems are:

- Windrow (static/quasi-static)
- Aerated static pile (static)
- Tunnel composting (quasi-static)
- In-Vessel (quasi-static)
- Rotary Drum (dynamic)

Today, the most common combination is a closed composting system with exhausted air treatment (retention time of about 2 weeks) for the intensive rotting, coupled with an open windrow composting (but roofed) for the post-rotting (retention time about 4 weeks).

The version with the lowest level of technology would be an open windrow composting without a roof, mechanical turning or technical aeration. Investment and operational costs for such systems are minimal, but come at the expense of product quality and odor emissions. And ultimately, the whole process depends on the climate conditions (temperature and precipitation).

Closed systems can be realized with basic techniques as well, and an example is the “chimney process” after Spillmann/Collins, which is described in Section 3.3.1. Closed systems have the advantage that the operational parameters can be optimized, the retention time can be shorten, emissions can be collected/treated, and the product quality can be improved.

3.4.1 Tunnel Composting + Windrow Post Rotting

We chose to suggest a composting plant with intensive rotting tunnel and windrow post rotting for the “high tech” version. A possible flowchart is shown in Figure 18 using data oriented on a composting plant in Germany with a yearly input of 22.000 t (Kompostwerk Mechernich).

For this process to be successful, it is necessary to collect the organic waste separately while fish and meat should not be included. In the delivery hall, about 25 vol-% of the structure material from park and garden wastes is mixed with the delivered waste. After a mechanical pre-treatment, the rotting material is put into rotting tunnels. The composting plant Mechernich, has 10 such tunnels, with sizes of l = 20.3m; w = 3.5m and h = 4.5m. The aerated concrete bottom is accessible with wheel loaders. For the optimal aerating process an approximately 20cm high field of structure material is laid on the aerating bottom before putting the waste on top. To avoid short-circuit fluxes, a 30cm wide gap is left between each wall. After closing the tunnel, the rotting material should be left for 14 days. The operational parameters are regulated with a process control system. The post rotting takes 4 weeks and the windrows are turned mechanically once a week. The finished compost is refined in a post mechanical treatment step, using a mobile trommel sieve with an air classifier which includes a discharge belt to separate impurities and sieve the fine grained and middle grained compost. The exhausted air from all halls and the rotting tunnels are treated trough a biological filter. [Bundesgütegemeinschaft Kompost e.V. 2003]

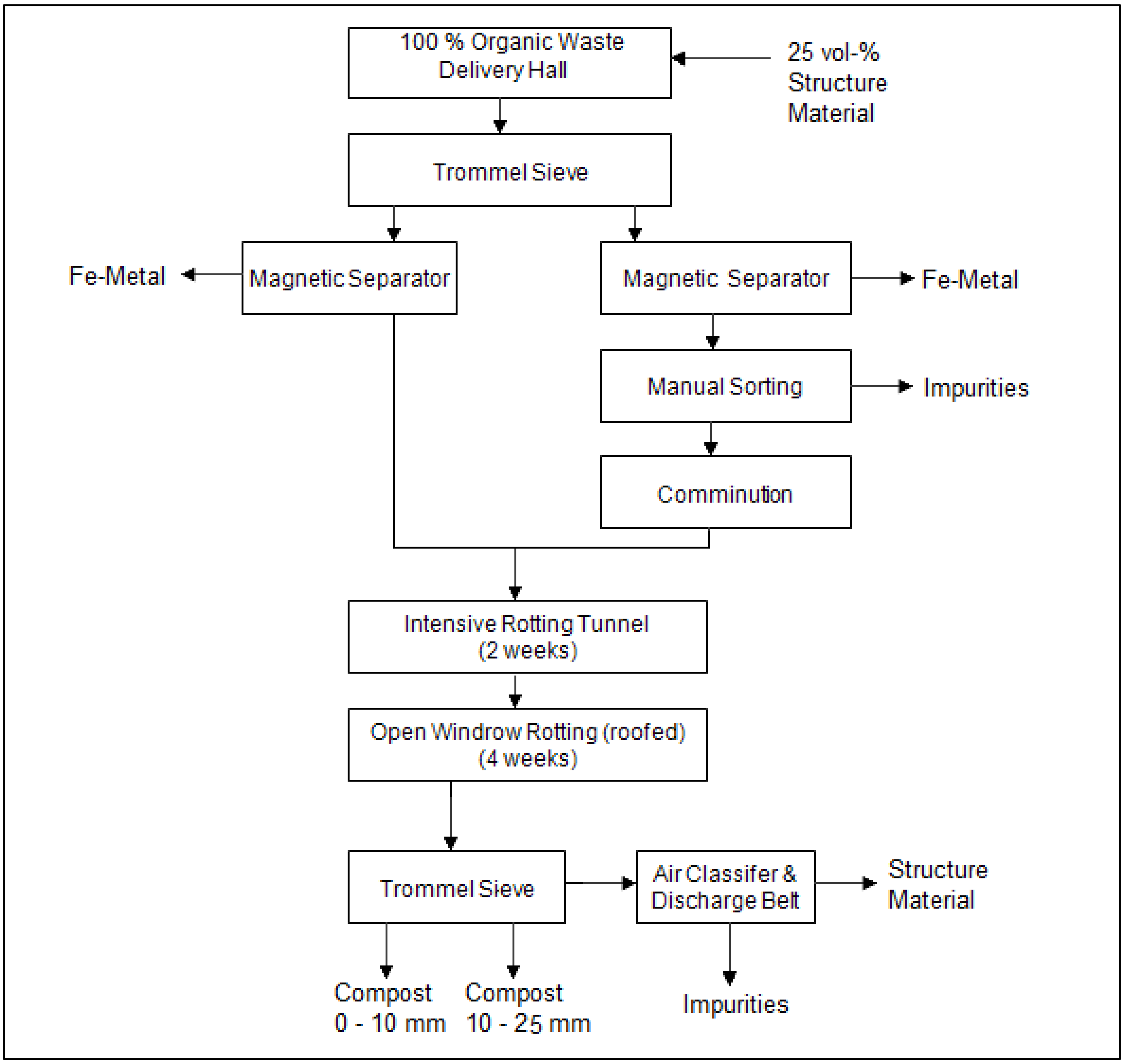


Figure 18: Flowchart of the composting plant Mechernich

The mass flow of the composting process, water content, and volatile dry matter can be taken from the Sankey chart in Figure 19.

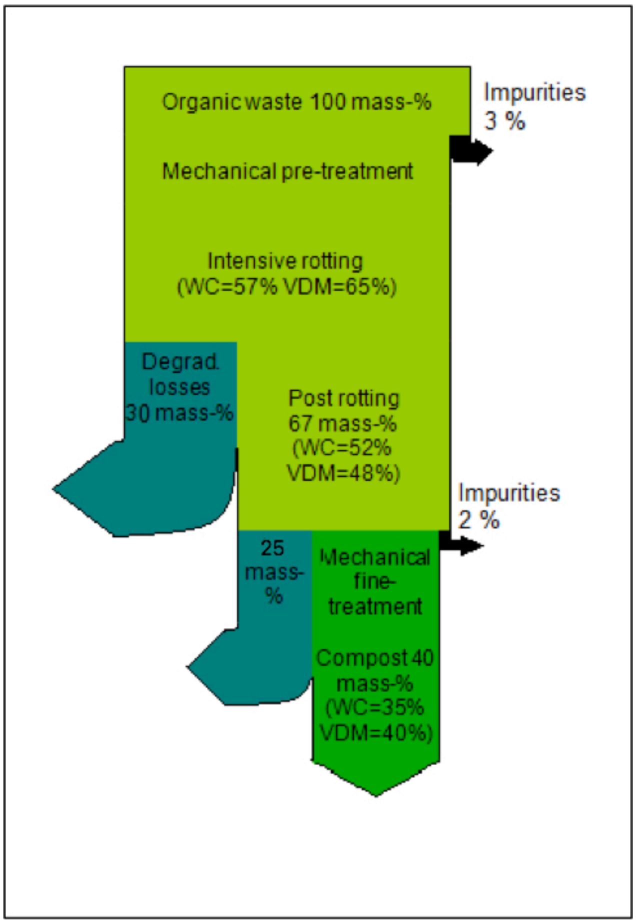


Figure 19: Sankey chart of composting process after [Thomé-Kozmiensky 1995]

3.5 Anaerobic Digestion

Anaerobic digestion is not a new technology, and is a common method to produce biogas, either as a part of sewage treatment in the water industry or for the treatment of agricultural and bio-waste. It is another way of naturally decomposing organic matter into its simpler chemical constituents. As “anaerobic” already describes in its name, this process happens under oxygen absence conditions.

Advantages of anaerobic digestion are:

- Biogas is a renewable energy and saves fossil fuels
- It prevents CO_2 emissions (climate neutral energy)
- Nutrients go back into the natural cycles
- Producing biogas meets the requirements for a sustainable future

Figure 20 shows a generalized process flow chart, which gives an overview of the municipal solid waste treatment by this method. There are different operating regimes and digester designs, which may vary the details of this procedure.

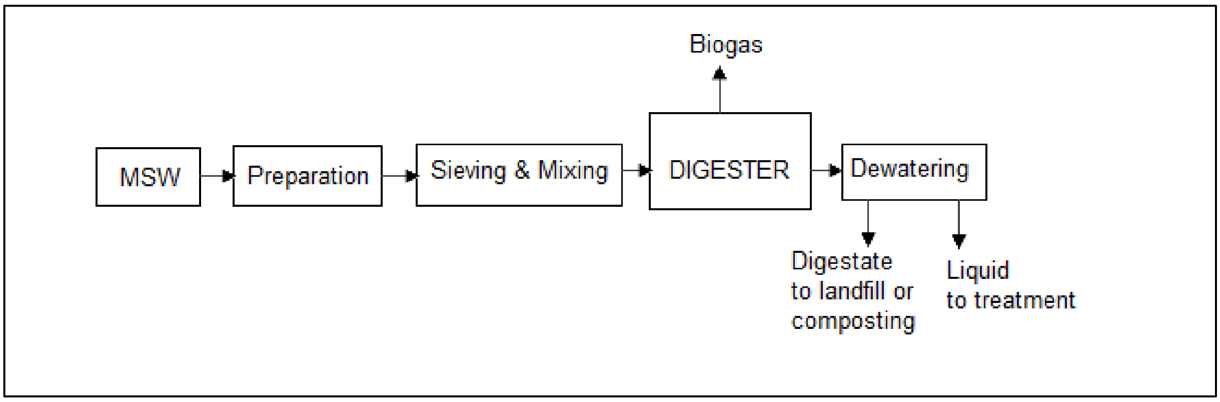


Figure 20: Generalized process flowchart of anaerobic digestion after [Evans 2001]

Anaerobic digestion is a very complex process in which many different bacteria are responsible for the break down of the large molecules of organic matter. What happens on microscopic level is not fully known. There are hundreds of potential intermediary reactions and compounds involved, but it is possible to simplify the overall biochemical reaction to:

$$\text{Organic matter} \xrightarrow{\text{anaerobic microorg.}} CH_4 + CO_2 + H_2 + NH_3 + H_2S$$

This conversion is possible because of the collaboration of specific bacteria groups:

- Fermentative Bacteria
- Acetogenic Bacteria
- Methanogenic Bacteria
- (Anaerobic fungi)

There are three main stages of anaerobic digestion and methanisation, which are:

- Hydrolysis
- Acidogenesis
- Methanogenesis

The optimal internal environment in a digester is summarized in Table 4. It can be a very challenging job to achieve this optimal environment, because these operational parameters are not the same for the different stages. For this reason, some anaerobic digestion plants have more than one digester. If the hydrolysis is separated in a spare vessel the parameters can be optimized for the different bacteria and will be less sensitive towards disturbances. There are a number of process variables which influence the anaerobic digestion. Physical factors include the digester mixing, temperature, retention period, wetness, digester loading, and bacterial population. Chemical factors include the pH, alkalinity and volatile fatty acids concentration.

Table 4: Operational parameters for anaerobic digestion [after Dornack 2016]

Parameter		Remark
C/N ratio	≈ 20	Optimal bacteria growth
pH	≈ 5.2 – 6.3	Fermentative bacteria
	≈ 6.8 – 7.2	Methanogenic/acetogenic bacteria
DM	< 15 %	Wet fermentation
	15% – 35%	Dry fermentation
Size of pieces	2 – 3 cm	

There are a wide range of anaerobic digesters which can be categorized in terms of their operating criteria. One criteria is the liquid ratio, which leads to their classification of “wet” or “dry.” This can be confusing, considering every digester needs some amount of wetness to produce biogas. Digesters with a loading of below 15% dry matter (DM), which are termed “wet” and above 15% are termed “dry”. Another distinction between the technologies, is the operating temperature, which is usually ca. 35°C (mesophilic) or ca. 55°C (thermophilic). The final categorization is on the basis of the regime of loading: “batch” or “continuous”. [Evans 2001]

Every system has advantages and disadvantages. Different types of digester can handle different types of biomass more effectively (sewage sludge, manure, organics from MSW etc.). Finding the right anaerobic digestion system depends on many factors, most of them are highly specific to the proposed location itself.

For these reasons it is not easy to make a general statement about how much biogas will be produced and how much digestion will occur. German anaerobic digestion plants for organics from MSW can gain 80 – 140 m^3/t biogas per tonne of waste, with a methane concentration of 50 – 60%. This corresponds to 50 – 80 m^3 of natural gas [Witzenhausen Institut 2012].

Biogas is mostly converted to electricity and heat through a CHP, resulting in approximately 200 – 300 kWh/t_{Input} of electricity and the same amount of heat (200 – 300 kWh/t_{Input}). The digestate can also be used as liquid fertilizer in agriculture. [Witzenhausen Institut 2012]

3.5.1 Two-Step Digestion

Good results for digesting organics from MSW were achieved with wet mesophilic two-step digesters. It is critical to have a good operating management, with skilled staff and the experience of working with microorganisms, which are sensitive to changes in the ambient conditions.

There are many different options of variations, which can generate different results. The following output streams are one possible outcome for organic waste treated in a wet mesophilic two-step digestion system:

-	impurities from pre-treatment	9 mass-%
-	wastewater	55 mass-%
-	digestate	20 mass-%
-	biogas	15 mass-%

[Bilitewski 2013]

Figure 21 shows a generalized anaerobic digestion plant. After the anaerobic digestion, a post-rotting step is placed. The combination of anaerobic digestion and composting is the most efficient biological treatment according to the research results of *Witzenhausen-Institut 2012.*

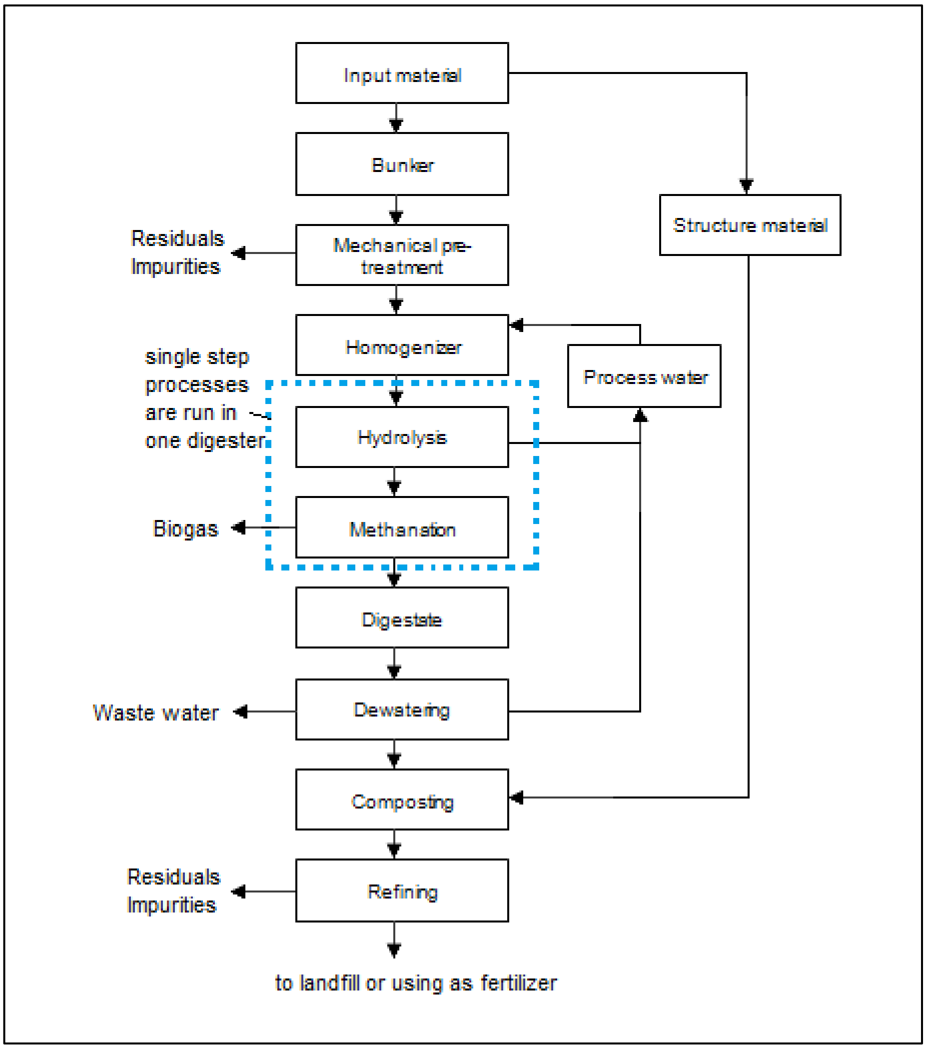


Figure 21: Generalized flowchart of an anaerobic digestion plant after [UBA 2014]

3.6 Incineration

Three different types of incinerations exist:

- Grate-firing
- Fluidized bed
- Rotary kiln

In this thesis, the focus will be on the grate-firing incineration, which as the name indicates, burns waste on a grate in a combustion chamber. Grate-firing incineration is a suitable and common treatment for MSW and has the opportunity of energy production. The essential requirements for grate-firing incineration are:

- Quality of input material:
  LCV = > 6,5 MJ/kg and < 12 MJ/kg
  grain size < 300 mm
- Flue gas cleaning
- It is preferable to have external customers, who can use the thermal energy (steam or warm water)
  → alternatively or additionally: a connection to the public power grid to feed in electricity

[UBA 2014]

Flue ash, bottom ash and flue gas are the three main output streams. The quality requirements for those are a TOC < 3 mass-% and in modern facilities a LOI can be achieved < 0,5 mass-%. [UBA 2014]

The biggest advantages for incinerating waste are:

- maximal reduction of the volume
- minimal pollutants and reaction potential of the bottom ash left
- possibility of energy production

Disadvantages include the high investment costs (in particular the costs for the guarantee of protection requirements) and problems with the acceptance of the population.

The grate-firing is a continuous process (24 hours), but the waste is delivered discontinuously (only during day time). For this reason, grate-firing incineration plants have an underground bunker with sufficient capacity. Furthermore it is used for mixing and homogenizing the waste with a grab crane to have a nearly constant calorific value.

In general, the burning of the waste happens between 850°-950°C. As the grate moves slowly, the bottom ash falls off the grate and into the bottom ash chamber beneath the grate. The flue gasses arises in the secondary combustion chamber, where it is cauterize by temperatures between 850°-1000°C. The flue gas cools down to 200°-400°C in a subsequent boiler. During this process, overheated steam is generated (max. 40 bar, 400°C), which is used to drive a turbine to produce electricity. [Bilitewski 2013]

Despite wastewater being produced from the steam boiler, the outputs per tonne waste input are:

- 260 – 350 kg/t bottom ash (26 – 35%)
- 5 - 20 kg/t flue ash (5 – 20%)
- 4,500 – 6,000 m^3 flue gasses

[UBA 2014]

Energy balance:

- Input: - MSW 100%
  - auxiliary fuel < 3% of the input of MSW
- Output: - Electricity with a generation efficiency up to 20% (on-site power subtracted)
  - Heat with a generation efficiency up to 60%

[UBA 2014]

Most incineration plants produce a combination of electricity and heat. However, using the generated heat means a smaller potential for electricity production.

Because of the regenerative compounds in the waste, incineration plants achieve a positive CO_2-balance.

The bottom ash can be landfilled on landfills of class II, but the residuals of the flue gas cleaning, including the flue ash, is declared as hazardous waste. A class III landfill would be more suitable. In Germany, for example, it is forbidden to landfill the residuals into a class II landfill such as those found in section 3.2, and a landfill class III for hazardous wastes is required.

The flue gas needs to be cleaned. The release of untreated flue gas would mean a high health risk for residents. State of the art of flue gas treatment is common, which are well-advanced and result in harmless outputs. There are many different units and technologies, which can be used to eliminate and reduce the following pollutants:

- organic carbon
- carbon monoxide (CO)
- sulfur oxides (SO_x)
- nitrogen oxides (NO_x)
- dioxins and furans
- heavy metals
- dust

4 Costs

Most of the costs depend on the local markets. In this thesis, we do not have sufficient information about the real costs and the actual circumstances in the case study regions, but we are able to give an overview of the investment and operational costs for each treatment. These assumptions can be taken as benchmarks but for a summarizing cost calculation, several other factors would need to be considered: For example, the time of operation, the collecting systems and hence transport costs, the actual costs of energy consumptions, staff costs, revenues and a lot more.

As a first overview, the assumptions by *Economopoulos 2012* are shown in Figure 22. The investment cost for the incineration are significantly higher than for an MBT, the operational costs are comparatively smaller and the specific costs per tonne input of waste decreases with increasing capacities.

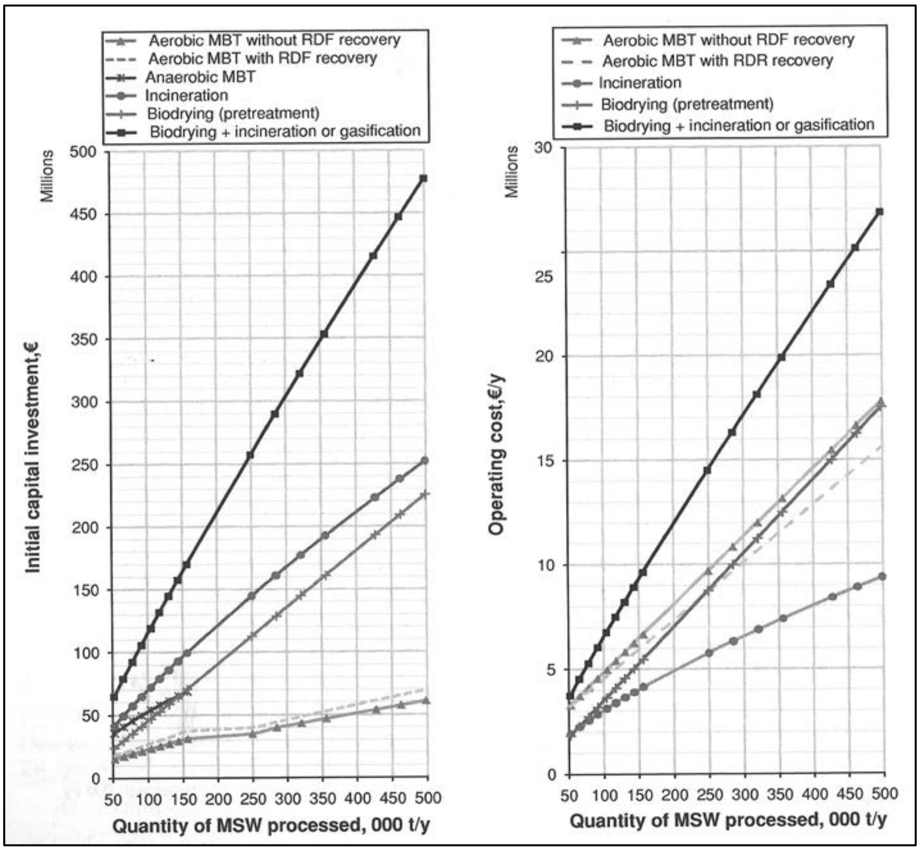


Figure 22: Initial capital investment and annual operating cost of waste treatment technologies [Economopoulos 2012]

4.1 Landfill Costs

The total charges for a sanitary landfill are composed of the following costs:

- investment costs
- operational costs
- post-closure costs

There are different calculations for the total costs in literature. A logical first step is to compare two cost calculation for a landfill using the following design data:

- yearly input: 110,000 m^3
- lifetime: 20 years
- area requirement: 200,000 m^2
- landfill body height 15 m
- post closure care 30 years

Table 3 shows the investment costs according to *Bilitewski 1994*, the prices are based from the year 1990/91 and in the former German currency DM.

Table 5: Capital requirements of a sanitary landfill after [Bilitewski 1994] (DM prices from 1990/91)

	Capital requirements in DM
Property	10,000,000
Site search/expert opinions/authorization	6,900,000
Development costs	2,350,000
Buildings	4,000,000
Base lining	22,000,000
Leachate collection	40,500,000
Leachate treatment	45,000,000
Degassing	3,500,000
Surface cover	39,000,000
Recultivation	3,000,000
Site vehicles / truck scale	3,840,000
Electrical technology	1,050,000
Total	181,140,000
Financing	10,745,000
Capital requirements	191,885,000

Bilitewski also gives an overview of the estimated operational costs of a landfill. The annual operational costs, also based on the year 1991, are approximately 3,123,000 DM [Bilitewski 1994].

The total costs in 20 years would be about 254 Mio. DM, which equals about 130 Mio € (if 1 DM = 0,51 €). With a total capacity of 1 Mio. m^3 waste the specific costs are 130 €/m^3.

The post-closure care cost for different landfills can be between 8 and 11 €/m^3 [Bilitewski 2013].

Those data leads us to our first assumption that total specific costs will be approximately 140 €/m^3.

A different literature reference uses the same facility data design and calculates using:

- investment costs: 12 Mio €/a
- surface cover 40 – 60 €/m^2
- operational cost: 1,8 Mio. €/a

[UBA 2014]

The investment costs are not completely unfolded, but they include a landfill gas collection and treatment facility, as well as, the post-closure care costs. Calculations made from this data bring total landfill costs to about 287 Mio. €, consequently the specific costs are about 287 €/m^3.

The specific costs depend a lot on the size of the landfill: compared to a bigger landfill a smaller landfill will have less operational and investment costs, but the specific investment cost in €/m^2 will be higher. This fact, however, was neglected from the calculations. In order to get more precise results, it is necessary to investigate the detailed current prices, which may differ in both regions.

The amounts in the D. Region, which may be landfilled, do not differ greatly between the scenarios and an average amount of 5,000 t/y for this region was calculated. The amount in the Mogilev region varies a little more, and an average of 40,000 t/y was calculated. The density of the output material of the MBT plant depends on many factors (input composition, kind of treatment, water content etc.), and because there is no defined term, the literature references 1.4 t/m^3 (for "high tech") and 1.2 t/m^3 (for "low tech") were used [Stief 1999, IFAS 2012, Fricke et al 1999].

<u>Assumptions for "High Tech" Landfill:</u>

- The design meets all the regulations for a class II landfill after German standards
- All six barriers meet the requirements
- Density of compacted infilled waste: 1.4 t/m^3
- Data for costs used after *UBA 2014*
- Landfill gas is collected and used in a CHP (cost savings not considered)

<u>Assumptions for "Low Tech":</u>

- Instead of an active degassing system a methane oxidation layer will be installed:
  ca. 50 % of the methane emissions can be oxidized to CO_2
  lower investment costs
  no revenues from CHP
  more released emissions
- Other barriers meet the requirements
- Density of compacted infilled waste: 1.2 t/m^3 (due to lower technology in compacting the waste, quality of MBT output)
- Data for costs used from *Bilitewski 1994*

Results of the cost calculations are shown in Table 4, detailed calculations can be found on the Annex-CD.

Table 6: Landfill costs for "low tech" and "high tech" versions

	D. 5,000 t/y	Mogilev 40,000 t/y
"low tech"	≈ 11.6 Mio € total costs	≈ 93.3 Mio € total costs
"high tech"	≈ 20.5 Mio € total costs	≈ 164 Mio € total costs

There are diverging opinions on the necessity of a gas collection system on landfills when the material is already pre-treated. Compared to a non-engineered landfill and a mechanical-biological pre-treatment, the greenhouse gas emissions are already 80 – 90% reduced [IFAS 2012]. The results of calculations of the emissions can be found in Chapter 4, the maximal methane emissions are measured with the maximum TOC of 18 mass-%.

4.2 MBT Costs

The main investment costs for an MBT include:

- Costs for site search, development costs
  if the MBT is a pre-treatment on a landfill site this costs will be significant smaller
- Equipment

mechanical component:	buildings (incl. delivery hall):	40 €/t
	stationary units:	20-80 €/t
	mobile equipment:	5-10 €/t
- biological component:	<u>rotting:</u>	
	building components:	70-90 €/t
	stationary units:	110-140 €/t
	<u>anaerobic digestion:</u>	
	building components:	50-60 €/t
	stationary units:	130-180 €/t

[UBA 2014]

Rough calculations of the total investment costs for an MBT plant in Europe are:

12 Mio € with 50,000 t/y capacity

40 Mio € with 220,000 t/y capacity

[UBA 2014]

Low tech MBTs with simple processing lines located on a landfill site in less capital-intensive countries can be realized with an investment of approximately 15 – 20 €/t [UBA 2014].

Operational costs include:

- Staff costs
- Electricity
- Insurance
- Service costs.

According to *UBA 2014*, the operational costs for the treatment with MBT are in the range of 40 – 100 €/t (calculations without revenues from RDF and metals or further disposal costs). No further considerations are made.

The estimated investment costs for both regions and the different scenarios with the previously discussed assumptions are shown in Table 8 (detailed calculations can be found in on the Annex-CD).

Table 7: Investment Costs for MBT

	Input [t/y]	Low Tech	on landfill site or ZUBR	High Tech
D.	11,200 – 15,200	2.7 – 3.7 Mio €	0.22 – 0.3 Mio €	4.0 – 5.4 Mio €
Mogilev	112,000 – 152,800	27- 37 Mio €	2.2 -3.1 Mio €	40 – 55 Mio €

These results are based on the assumptions that the throughput amounts and investment costs are proportional.

The “low tech” calculations after German standards are ten times higher than those of a simple processing line on a landfill designed for less capital-intensive countries. Realistically, the true amount is somewhere in between the two. The investment costs for the MBT Kahlenberg (47 Mio €) is exactly in the middle of the range of the costs for a “high tech” version for Mogilev region. The calculations are a rough benchmark, and should be considered with caution. However, it confirms that the throughput is a key factor in the facility design.

4.3 Composting Costs

The investment costs for the described composting plant in Section 3.4.1 were about 7,5 Mio € [Bundesgütegemeinschaft Kompost e.V. 2003]. The costs for the MBT, associated with the rotting process were already characterized in Section 4.2. A “low tech” facility can be realized with less investment costs. In Germany, the mass specific costs for a composting plant can be in the range of 40-110 €/t. Tunnel intensive rotting plants being more economical with a throughput from 3,000 t/a. [UBA 2014]

4.4 Anaerobic Digestion Costs

The anaerobic digestion is just part of one scenario of the case studies, in the scenario S4 of Mogilev region, the throughput amount is 23,600 t/y. The specific total costs per tonne for an anaerobic digestion facility with a capacity of 20,000 t/y are in the range of 50-100 €/t [UBA 2014]. When considering the revenues generated from electricity and compost these costs decrease.

According to the *UBA 2014*, the investment costs of a facility with 23,600 t/y input may be between 5.9 Mio € - 13 Mio €, plus the yearly operational costs of 1.8 Mio € - 3.1 Mio €.

4.5 Incineration Costs

The following assumptions about investment and operational costs are based on a very general level.

Table 8: Investment costs for an incineration with a throughput of 200,000 t/y [UBA 2014]

Grate-firing Incineration	
Development costs	1 Mio €
Underground bunker	4 Mio €
Other buildings	6.5 Mio €
Boiler and steam generator	32 Mio €
Alternator	4 Mio €
Construction and capital costs	7 Mio €
Flue gas cleaning	
Construction Costs	4.5 Mio €
Equipment	13 Mio €
Other costs	3.5 Mio €
Total	75.5 Mio €

In addition to the investment costs, come the operational cost, which depend immensely on the market price of the supplies and local staff costs. Approximately 1 % of the investment costs for each component and 3 – 4 % of the investment costs for machines and electrical technology can be assumed to be needed for repairs and maintenance costs. [UBA 2014]

According to the *UBA 2014,* the total specific cost per mass were in a range between 80 – 250 €. This coincides with the average specific costs per mass of 137 €/t for different incinerations in Germany [Bilitweski 2013].

5 Greenhouse Gas Emissions

Finally, the focus is on the balance of the greenhouse gases. In the following section, we present our results for the different scenarios. The calculations were made with the unpublished Emission-Calculation-Tool from the Institute of Waste Management and Circular Economy (TU Dresden). It was necessary to make several assumptions and simplifications. A detailed description of the technologies used can be found in each chapter of the facility design. The most important data that was used is summarized below:

<u>General data and assumptions used for the calculations:</u>

- CH_4 has a 21 times higher greenhouse gas potential than CO_2
- N_2O has a 310 times higher greenhouse gas potential than CO_2
- Density of methane 0.72 kg/m^3
- 55% of the total landfill gas is methane
- 60% of the biogas from anaerobic digestion is methane
- CH_4 has an energy content of 10 kWh (LCV = 50 MJ/kg)
- All RDF produced is co-incinerated in power plants with an electric efficiency of 38%

<u>Landfill</u>

"Low Tech"

- TOC ≤ 18 mass-%
- No gas collection
- Methane oxidation 50%

"High Tech"

- TOC ≤ 18 mass-%
- Landfill gas collection
- CHP with 35% electrical efficiency power unit (net)
- CHP with 10% thermal efficiency power unit (net)
- Methane recovery factor 60%
- Methane oxidation 10%

<u>MBT</u>

"Low Tech"

- Impurities 5%
- Metals 2%
- RDF 35%
- Degradation 18%
- Treated material to landfill 40%

"High Tech"

- RDF 35%
- Biogas 7%
- Metals 2%
- Treated material to landfill 14%
- Waste water and degradation losses 42%

Composting

- Impurities 5%
- Degradation losses 55%
- Compost 40%

In the composting process, the organic matter is decomposed into H_2O and CO_2. The CO_2 is climate neutral. The avoided GHG is included in the calculations indirectly through the decreased input amounts and the lower organic compounds in the waste composition.

Incineration

- Grate-firing incineration plant	
- Efficiency of incineration	97%
- Concentration N_2O in mg/Nm^3	2
- Flue gas volume in Nm^3/Mg input	5,500
- Auxiliary fuel	
fuel oil in % of thermal input	2%
natural gas in % of thermal	0.5%

Version 1:

- Electrical net efficiency	10%
- Thermal net efficiency	35%

Version 2:

- Electrical net efficiency	30%
- Thermal net efficiency	0%

Anaerobic Digestion

- Output streams	
impurities from pre-treatment	5 mass-%
wastewater	60 mass-%
digestate	25 mass-%
biogas	10 mass-%
- Specific gas yield:	
Organic	500 Nm^3/t VDM
Wood	40 Nm^3/t VDM
- CHP	
electrical net efficiency	35%
thermal net efficiency	12%
- Own consumption	
electricity	50 kWh/t_{input}
heat	30 kWh/t_{input}
fuel oil/diesel	11 kWh/t_{input}

5.1 D. Region

The total estimated amount of MSW for the D. region in 2025 is 15,100 t, bulky waste, WEEE and hazardous waste not included. In the different scenarios, different amounts of recyclables and organics will be collected separately (s. Table 9). This will change the waste composition as described in Table 10. All calculations can be found on the Annex-CD.

Table 9: Separately collected recyclables and organics in D. region in [t/y]

	1a	1b	2a	2b	3a	3b
Organics				1.600	600	600
Glas	600	800	800	800	600	600
Fe/Ne Metals		200	200	200	200	200
Plastic	200	500	500	500		
Paper/Cardboard		900	800	800		
Total	800	2,400	2,300	3,900	800	1,600

Table 10: Waste compositions for the different scenarios in D. region in [mass-%]

	First step	1a	1b	2a	2b	3a	3b
Organic	20.00%	21.12%	23.78%	23.59%	12.68%	21.12%	17.66%
Wood	2.00%	2.11%	2.38%	2.36%	2.70%	2.11%	2.20%
Textiles	4.00%	4.22%	4.76%	4.72%	5.39%	4.22%	4.41%
Minerals	8.00%	8.45%	9.51%	9.44%	10.79%	8.45%	8.82%
Composits	5.00%	5.28%	5.94%	5.90%	6.74%	5.28%	5.51%
Pollutants	0.40%	0.42%	0.48%	0.47%	0.54%	0.42%	0.44%
Others	29.90%	31.57%	35.55%	35.27%	40.31%	31.57%	32.96%
Fine fraction <10mm	10.00%	10.56%	11.89%	11.80%	13.48%	10.56%	11.02%
Fe/Ne-Metalls	1.70%	1.80%	0.45%	0.44%	0.51%	0.40%	0.41%
Paper/Cardboard	7.00%	7.39%	1.24%	2.01%	2.29%	7.39%	7.72%
Glas	7.50%	3.72%	2.62%	2.60%	2.97%	3.72%	3.89%
Plastics	4.50%	3.35%	1.41%	1.40%	1.60%	4.75%	4.96%

Basically, the main differences between the 7 scenarios (first step included) of the D. region are the input amounts and the waste compositions of these inputs. We calculated the greenhouse gas emissions for the following versions:

Version 1: "low tech"

Calculations were made with the different input amounts and the different waste compositions for each of the 7 scenarios with the assumptions made for the "low tech" MBT and the "low tech" landfill.

Version 2: "high tech"

Calculations were made with the different input amounts and the different waste compositions for each of the 7 scenarios with the assumptions made for the "high tech" MBT and the "high tech" landfill.

Version 3: "first step scenario: MBT + Sanitary Landfill"

Calculations were made for different combinations of the variations for MBT and landfill with the input amount and waste composition of the first step scenario.

Version 1: "low tech"

Table 11 provides an overview of the GHG emissions which are released through the waste treatment as well as the avoided GHG emissions from energy recovery of the waste treatment or through recovery of recyclables. All avoided GHG emissions are provided as negative amounts. The released and avoided GHG can be balanced, the last column shows the net emissions.

Table 11: GHG emissions D. region Version 1 - "low tech"

	released GHG emissions t/y $CO_{2,eq.}$	avoided GHG emissions t/y $CO_{2,eq.}$	GHG net emissions t/y $CO_{2,eq.}$
First Step	7.732	-4.963	2.769
Scenario 1A	7.339	-4.717	2.622
Scenario 1B	6.265	-3.963	2.302
Scenario 2A	6.321	-4.011	2.310
Scenario 2B	5.474	-3.961	1.514
Scenario 3A	7.700	-5.157	2.544
Scenario 3B	7.374	-5.136	2.238

Fewer net emissions occur in Scenario 2B: "full recycling + composting" with an amount of 1,514 t of CO_2 equivalent. The RDF Scenarios 3A and 3B can avoid most of the GHG emissions compared to the other scenarios but unfortunately, these scenarios also release more GHG. Figure 23 shows the climate-relevant GHG balance of Scenario 2B and Figure 24 of Scenario 3A.

Following statements can be made:

- A higher MBT input and higher landfill input will release more GHG
- Fewer emissions will be released, with a smaller organic fraction in the waste composition
- Low usage of technology demands a higher effort of collecting the waste separately for reusing and recycling the material (composting included)

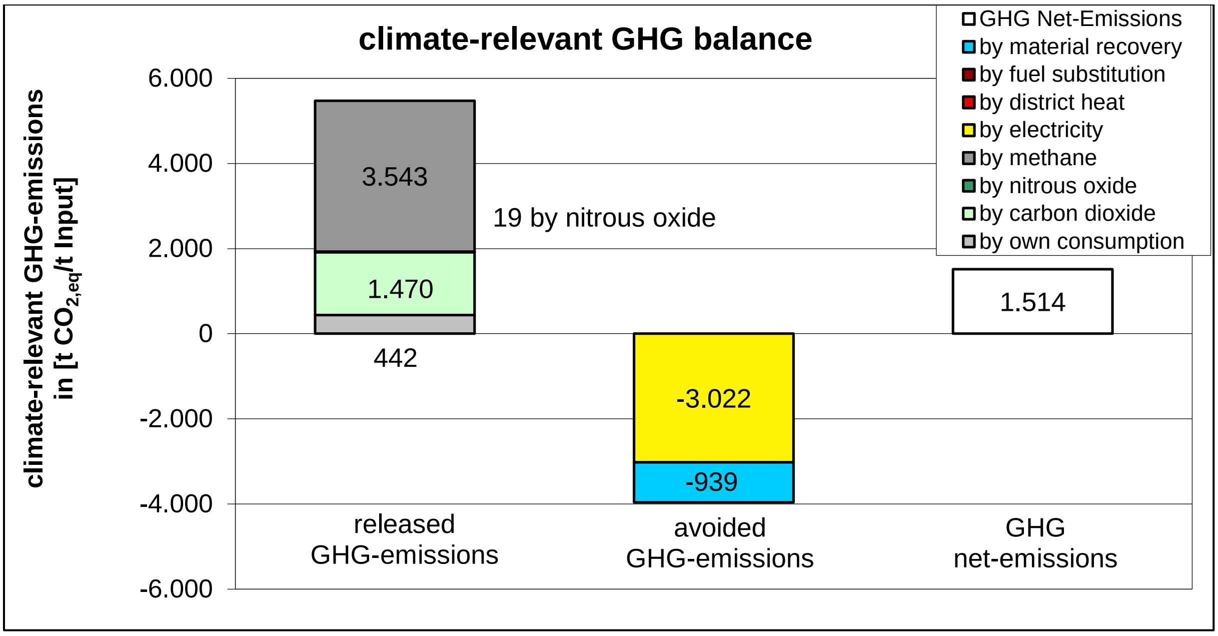


Figure 23: Scenario 2B, Version 1: "low tech" – Climate-relevant GHG balance

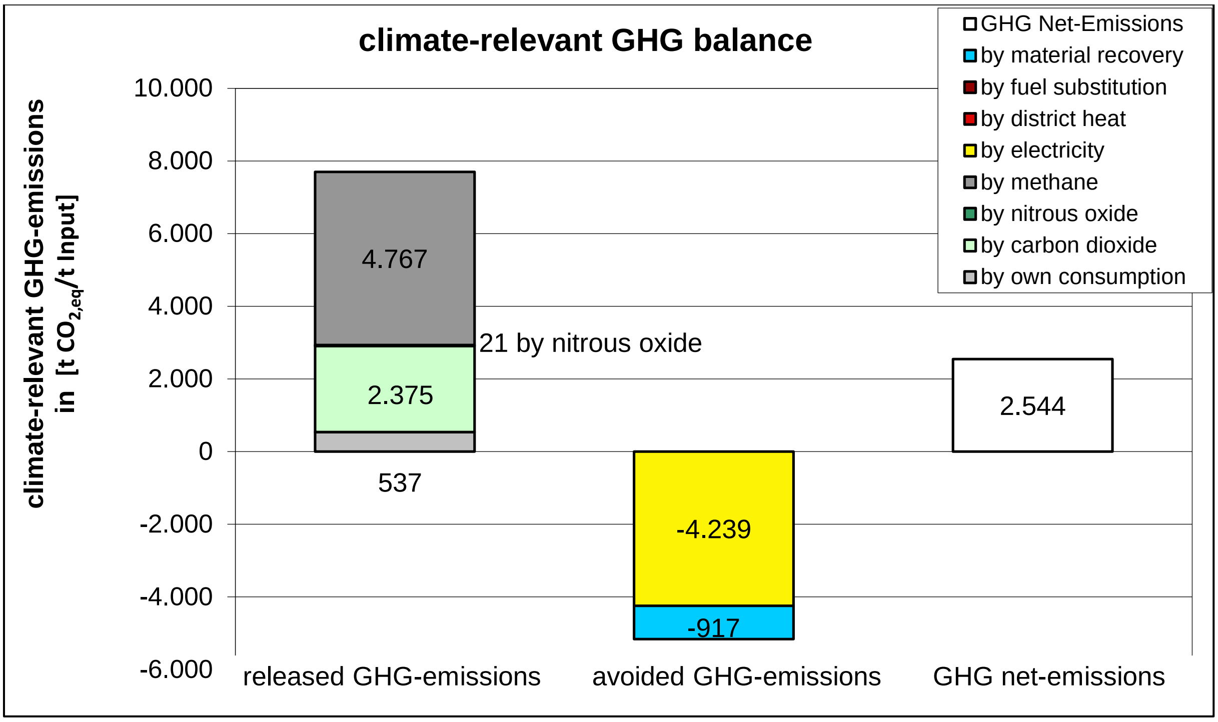


Figure 24: Scenario 3A, Version 1: "low tech" – Climate-relevant GHG balance

Version 2: “high tech”

The results of the versions “high tech” MBT and “high tech” landfill are shown in Table 12. All 7 scenarios have negative GHG net emissions. More GHG will be avoided than released, no matter which scenario is considered. Both facilities are using the resulting biogas to produce electricity and heat. The GHG balance does not depend on the waste composition in particular but on the total amount of the organic content.

Table 12: GHG emissions D. region Version 2 - "high tech"

	released GHG emissions t/y $CO_{2,eq.}$	avoided GHG emissions t/y $CO_{2,eq.}$	GHG net emissions t/y $CO_{2,eq.}$
First Step	5,156	-6,512	-1,355
Scenario 1A	5,259	-6,318	-1,059
Scenario 1B	4,330	-5,363	-1,033
Scenario 2A	4,360	-5,422	-1,062
Scenario 2B	3,714	-4,949	-1,235
Scenario 3A	5,689	-6,816	-1,127
Scenario 3B	5,546	-6,663	-1,118

As mentioned before, a high tech MBT would probably not be economical for these input amounts. Figure 25 describes the GHG balance of the MBT for the first step scenario and Figure 26 shows the balance for the 2B Scenario.

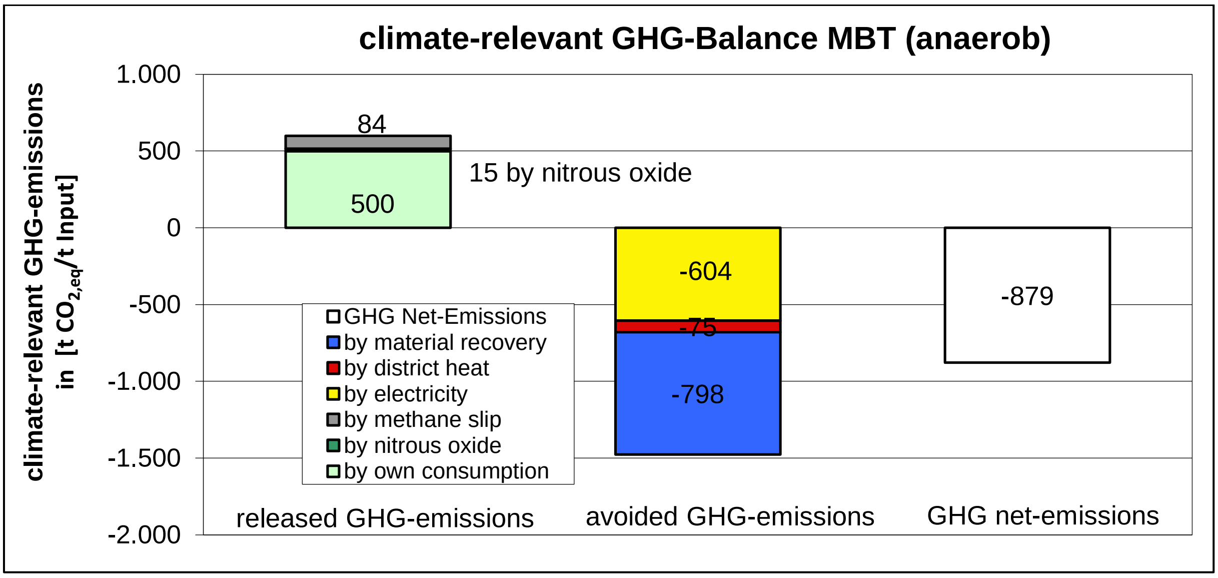


Figure 25: First Step Scenario, MBT: "high tech" – Climate-relevant GHG balance

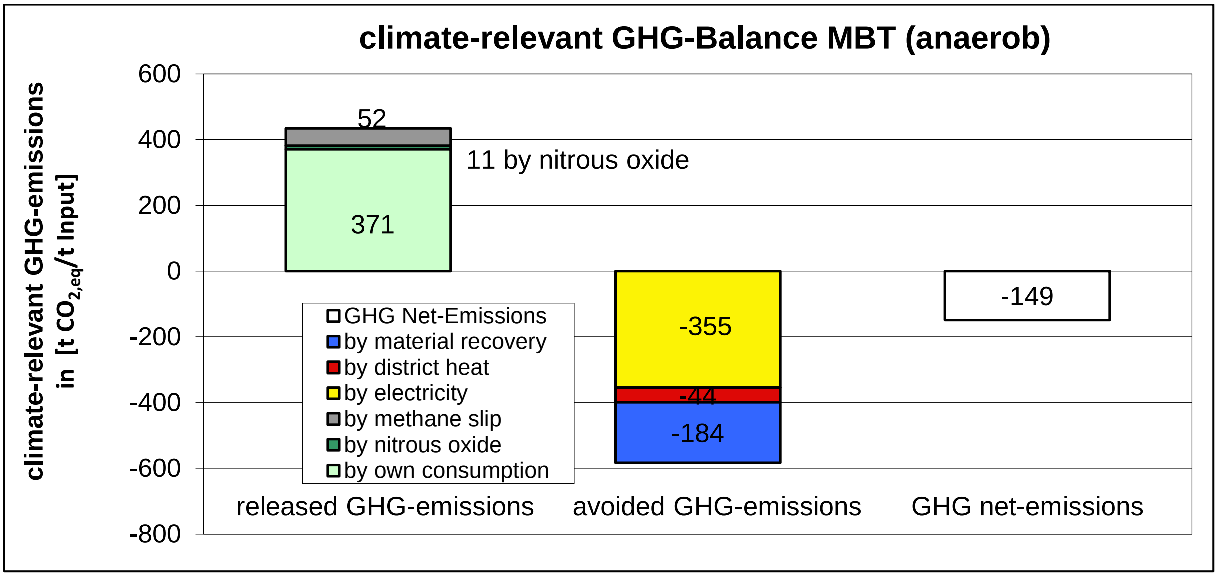


Figure 26: Scenario 2B, MBT: "high tech" – Climate-relevant GHG balance

We chose this comparison because according to Table 12 the scenario 2B is the one with the second highest net emissions. However, it is also the one with less avoided GHG. Thus it is clear that the results are just due to the low input amounts. We want to demonstrate this fact with the next two figures (27 and 28), in which the GHG balance for the MBT of these two scenarios is shown with an input amount of 100,000 t/y.

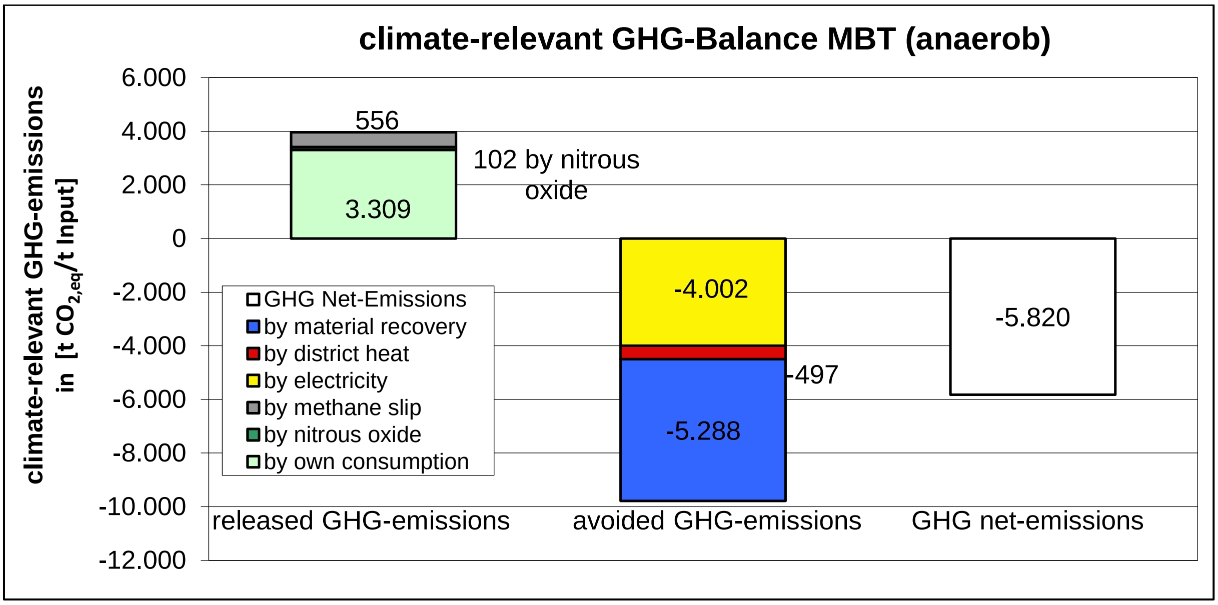


Figure 27: First Step Scenario, MBT: "high tech" – input amount 100.000 t/y

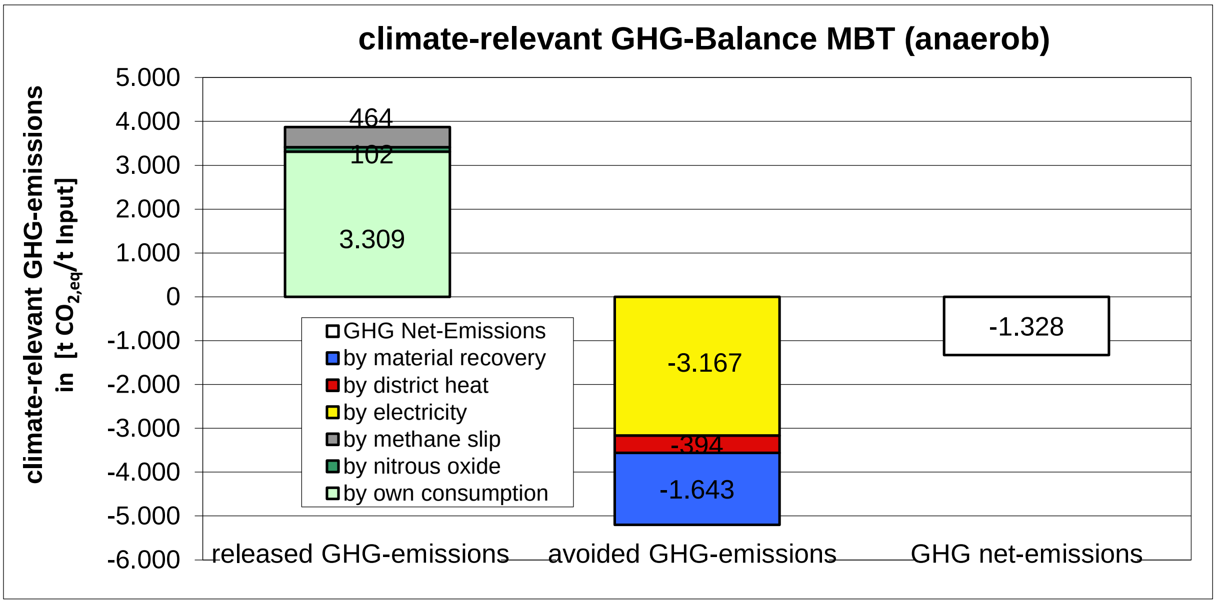


Figure 28: Scenario 2B, MBT: "high tech" – input amount 100.000 t/y

There is no big difference between the released GHG emissions, but the recovered energy and material recovery are clearly higher in the first step scenario. Hence, the GHG balance of the first step scenario is beneficial. Obviously, for this version it makes more sense to leave the recyclables and organics together with the residuals, in case of a high efficiency of energy and material recovery of the MBT. Especially the plastic, paper/cardboard, textiles and composites with a higher LCV for the high caloric fraction should not be collected separately. The RDF Scenarios 3A and 3B, which have a higher proportion of those fractions in their compositions, will also avoid the most GHG (cf. Table 11 and Table 12).

Version 3: First Step Scenario: MBT + Sanitary Landfill

All results for this version are based on the input amount of 15,100 t/y and the waste composition of the first step scenario. You can find the GHG balance for the different variations of combinations in Table 13.

Table 13: GHG emissions D. region Version 3 – First Step Scenario

	released GHG emissions t/y $CO_{2,eq.}$	avoided GHG emissions t/y $CO_{2,eq.}$	GHG net emissions t/y $CO_{2,eq.}$
"current situation" no MBT/ non-engineered landfill	21,088	0	21,088
no MBT/ low tech landfill	10,544	0	10,544
no MBT/landfill with gas collection	7,655	-1,926	5,729
low tech MBT/non-engineered landfill	12,499	-4,963	7,537
high tech MBT/non-engineered land-fill	8,432	-6,042	2,390
high tech MBT/low tech landfill	5,861	-6,042	-181
low tech MBT/high tech landfill	6,425	-5,834	591

If the current situation would still exist in 2025, a yearly amount of about 21,000 t $CO_{2,eq}$ would be released and no GHG would be avoided by any treatment. This amount could in fact be halved with an engineered landfill. If you compare the current situation with the first step scenario in version 1, you will see that the net emissions are just one-eighth of the “current situation” released GHG.

A negative net emission is achieved in the combination of a “high tech” MBT and a “low tech” landfill. But obviously, every treatment would improve the GHG balance.

5.2 Mogilev Region

For the Mogilev region, the total estimated amount of MSW in 2025 is about 163.900 t, bulky waste, WEEE and hazardous waste not included. In the different scenarios, different amounts of recyclables and organics will be collected separately (s. Table 14). This will change the waste composition as you can see in Table 15.

Table 14: Separately collected recyclables and organics in Mogilev region in [t/y]

	First Step	S1	S2	S3	S4
Organic	-	-	23,600	23,600	23,600
Fe/Ne-Metals	-	2,500	-	-	1,800
Paper/Cardboard	4,900	15,300	13,300	13,300	-
Glas	4,400	10,900	10,600	10,600	10,600
Plastics	1,800	4,700	4,400	4,400	-
Total	11,100	33,400	51,900	51,900	36,000

Table 15: Waste composition for the different scenarios in Mogilev region

	First Step	S1	S2	S3	S4
Organic	30.00%	35.13%	19.86%	19.86%	17.39%
Wood	5.00%	5.85%	6.82%	6.82%	5.97%
Textiles	3.00%	3.51%	4.09%	4.09%	3.58%
Minerals	8.00%	9.37%	10.91%	10.91%	9.56%
Composites	5.00%	5.85%	6.82%	6.82%	5.97%
Pollutants	1.00%	1.17%	1.36%	1.36%	1.19%
Others	18.00%	21.08%	24.56%	24.56%	21.50%
Fine fraction <10mm	10.00%	11.71%	13.64%	13.64%	11.95%
Fe/Ne-Metals	2.00%	0.43%	2.73%	2.73%	0.98%
Paper/Cardboard	8.00%	1.40%	3.41%	3.41%	13.39%
Glas	7.00%	3.22%	4.01%	4.01%	3.52%
Plastics	3.00%	1.29%	1.77%	1.77%	4.99%

The calculations for the Mogilev region scenarios are based on the same pattern that was used for the D. region. We will show two different versions for each scenario “low tech” and “high tech” but actually for scenario 3 and 4, there is no “low or high tech” variation. We decided that the incineration plant and the anaerobic digestion plant are kind of high technology treatments already and since we did not determine one specific facility, we will focus on the difference between the energy recovery of the incineration. Version 1 of the incineration plant will produce electricity with an efficiency of 10% and heat with an efficiency of 35%. Version 2 will only produce electricity with an efficiency of 30% and no heat at all. We made this decision because of the fact that electricity is the energy of higher value. It can be feed into the grid anytime and anywhere and when producing heat you will always need an external customer nearby, which can be difficult, especially when the incineration plant is located somewhere extramural.

Version 1: "low tech" resp. electricity and heat

Table 16 shows the first evaluation for the Mogilev scenarios. Just like the input amounts, the net emissions of the first step scenario for Mogilev region are 10 times higher compared to those of D. region. Hence, for the "low tech" variation and the first step (with just small amounts of separate collection) the GHG emissions are proportional to the input amounts.

Table 16: GHG emissions Mogilev region Version 1

Scenarios	released GHG emissions t/y $CO_{2,eq.}$	avoided GHG emissions t/y $CO_{2,eq.}$	GHG net emissions t/y $CO_{2,eq.}$
First Step	71,446	-49,177	22,270
S1	60,808	-41,563	19,245
S2	50,895	-39,958	10,938
S3	21,639	-31,971	-10,332
S4	33,129	-52,865	-19,737

Scenario S4 "full energy recovery" shows the best GHG balance with about -20,000 t $CO_{2,eq}$ per year. If we just look at the avoided GHG, the first step scenario can almost avoid the same amount but releases a lot more. In the next two figures (29 and 30), it becomes quite clear that the released GHG comes from the landfill. There is no big difference in regard to the emissions between the energy recovery through RDF co-incineration in a power plant and the waste incineration plant.

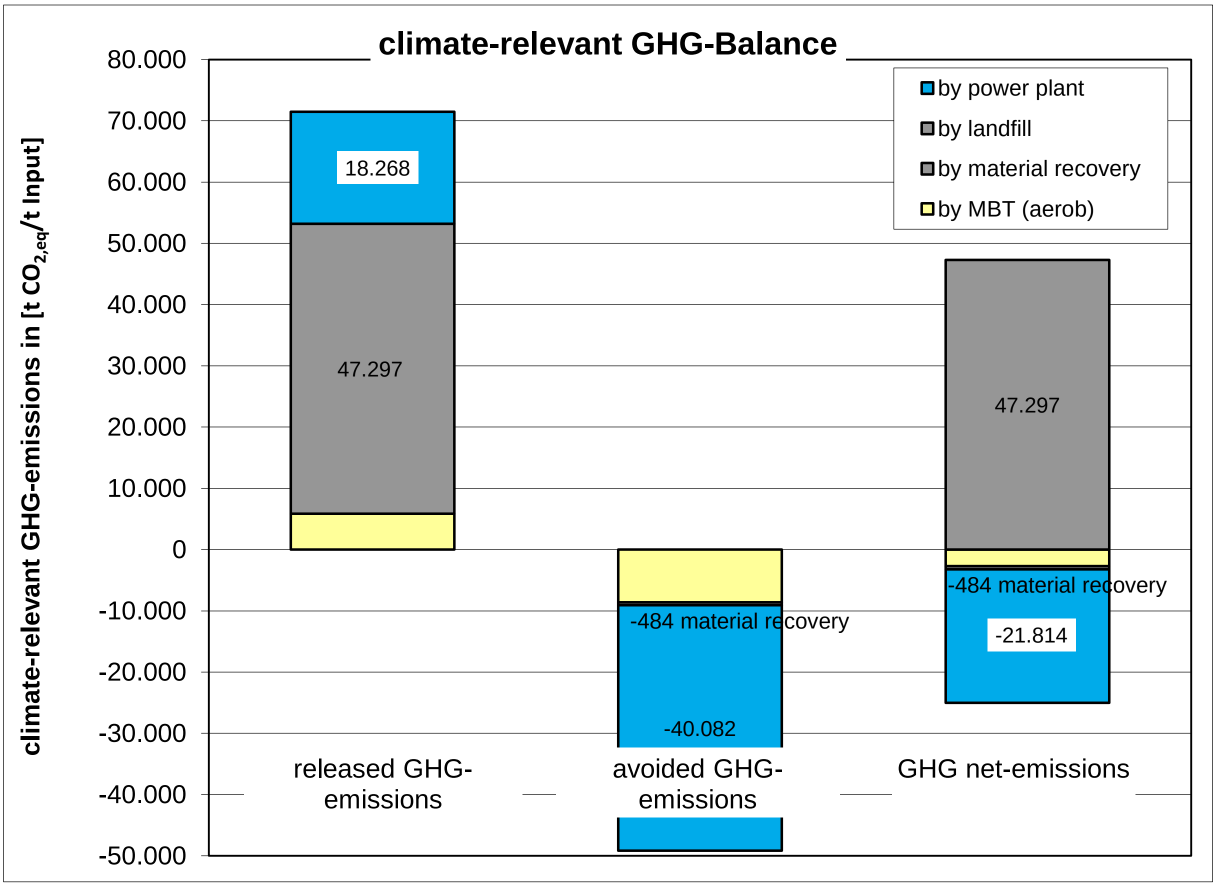


Figure 29: First Step Scenario, version 1 – Climate-relevant GHG balance by treatments

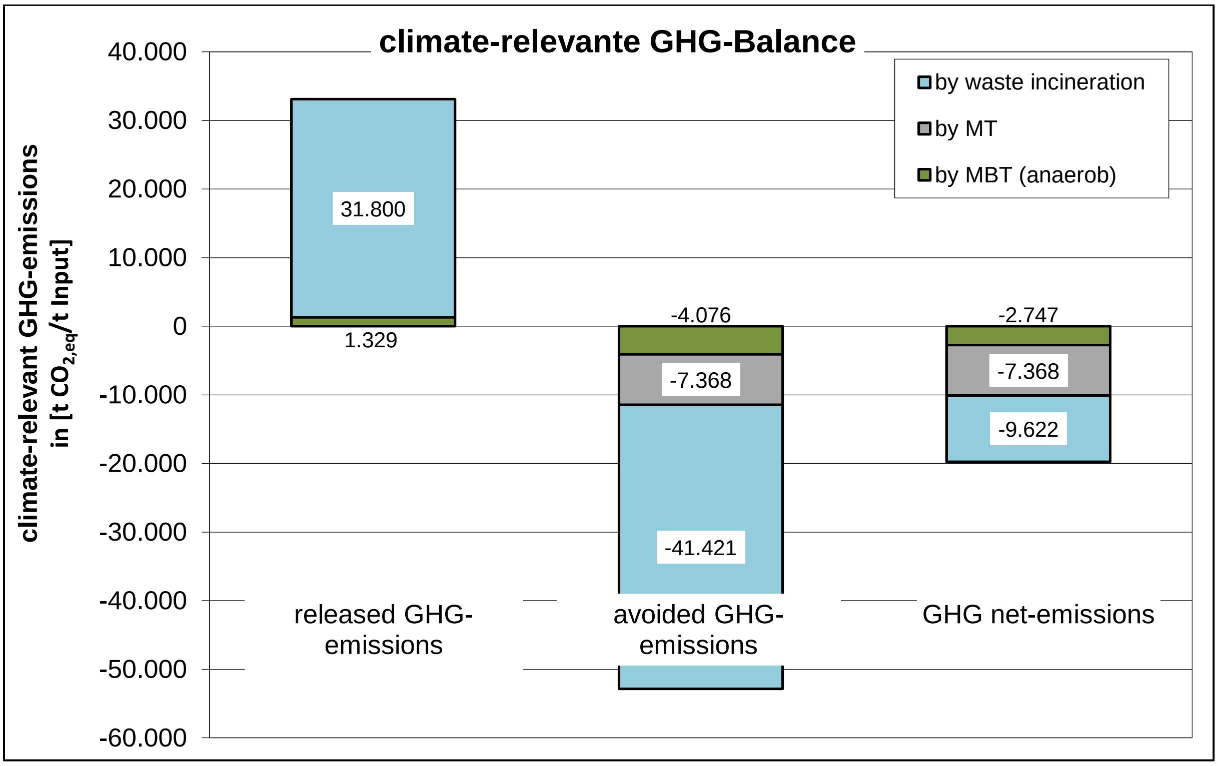


Figure 30: Scenario 4, version 1 – Climate-relevant GHG balance by treatments

Version 2: "high tech" resp. just electricity

In the "high tech" version, every scenario has negative net emissions. The first step and the Scenarios 1 and 2 can nearly achieve the same results as the scenarios with an incineration plant. The different versions of the energy production from incineration would be the best option for the Mogilev region if only the GHG net emissions were considered (Table 17).

Table 17: GHG emissions Mogilev region Version 2

Scenarios	released GHG emissions t/y $CO_{2,eq.}$	avoided GHG emissions t/y $CO_{2,eq.}$	GHG net emissions t/y $CO_{2,eq.}$
First Step	49.438	-66.609	-17.171
S1	40.613	-56.690	-16.077
S2	32.386	-49.830	-17.444
S3	21.639	-41.904	-20.266
S4	33.129	-66.223	-33.095

Scenario 2 and 3 have the same input amounts and the same waste composition. It exemplifies that a high tech MBT can nearly achieve the same net emissions, or even better results, in comparison to the electricity-heat-recovery combination in version 1.

As a last comparison of the GHG balance in Figure 31 and 32, the difference of the energy production of the waste incineration plants is shown for the two versions.

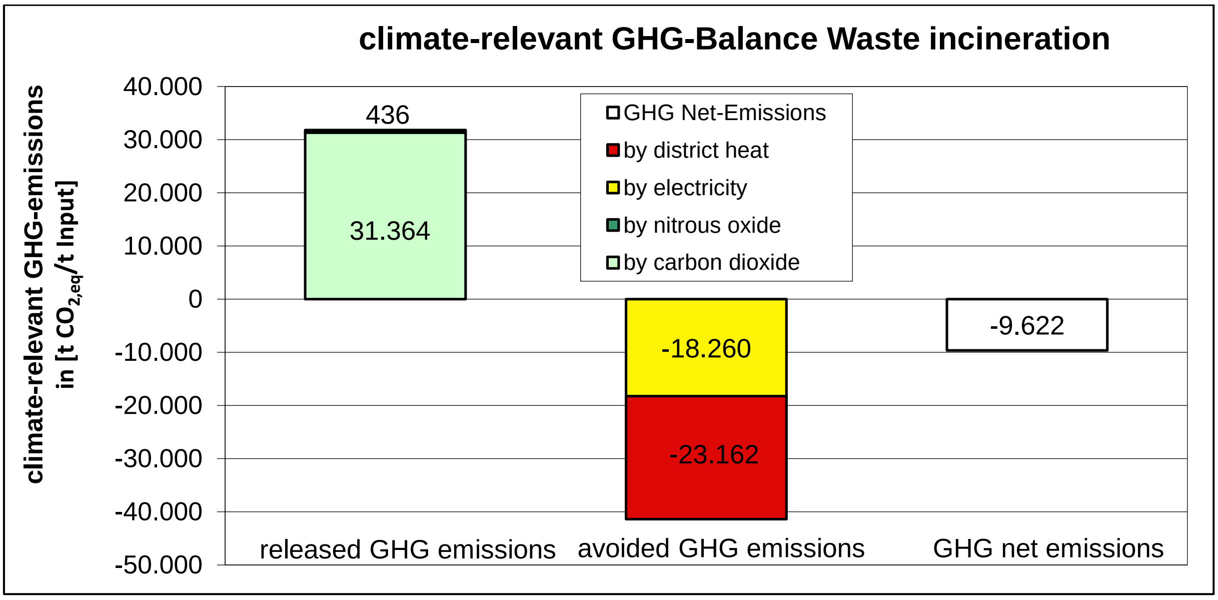


Figure 31: GHG Balance Waste Incineration Plant (10% electrical and 35% thermal net efficiency)

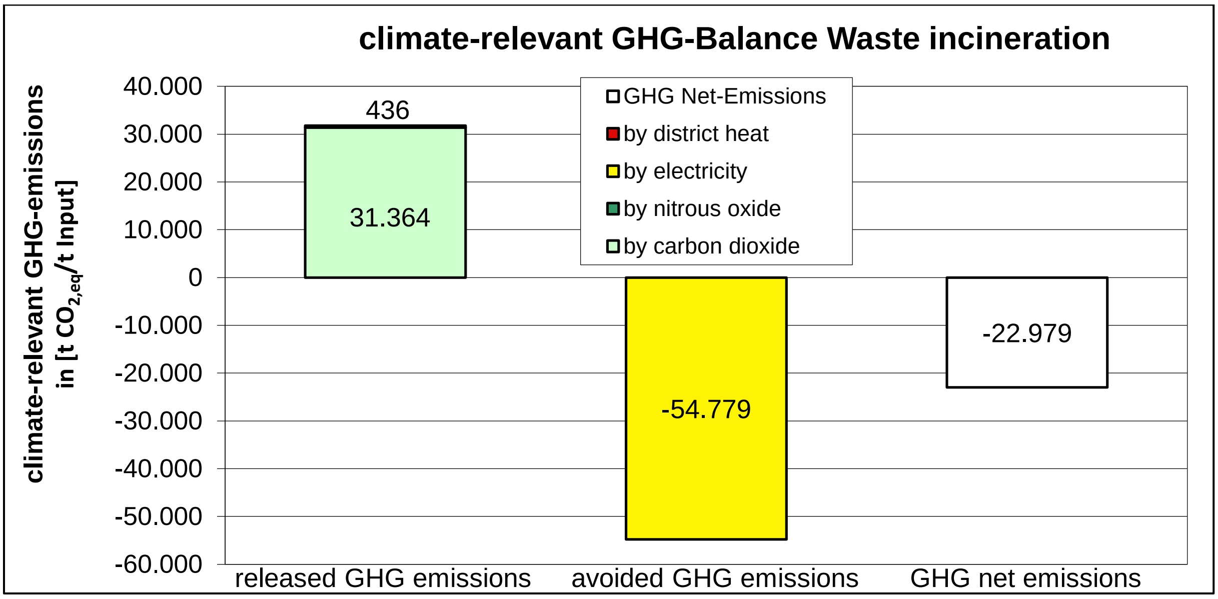


Figure 32: GHG Balance Waste Incineration Plant (30% electrical net efficiency)

Version 3: First step Scenario MBT + sanitary landfill

The results of the third version (Table 18) are based on an input amount of 152,800 t/y and the waste composition of the first step scenario. About 10,900 t/y recyclables are already collected separately in the first step scenario. This material recovery avoids about 500 t/y $CO_{2,eq.}$ GHG emissions. But without any further treatment and a non-engineered landfill only, about 230,000 t/y $CO_{2,eq.}$ will still be released in 2025. Apart from this, the same statements about version 3 of D. region can be repeated. With more technology, fewer net emissions will be released and the combination “high tech” MBT and “low-tech” landfill is even in negative net emissions.

Table 18: GHG emissions Mogilev region Version 3 – First Step Scenario

	released GHG emissions t/y $CO_{2,eq.}$	avoided GHG emissions t/y $CO_{2,eq.}$	GHG net emissions t/y $CO_{2,eq.}$
"current situation" no MBT/ non-engineered landfill	231,512	-484	231,028
no MBT/ low tech landfill	115,756	-484	115,272
no MBT/landfill with gas collection	84,039	-21,632	62,406
low tech MBT/non-engineered landfill	118,743	-49,177	69,567
high tech MBT/non-engineered land-fill	89,046	-60,929	28,117
high tech MBT/low tech landfill	57,956	-60,929	-2,972
low tech MBT/high tech landfill	58,487	-57,818	669

6 Conclusion

As repeatedly mentioned, the results presented in this thesis can be used as possible benchmarks, but are based on many assumptions. In this chapter, we want to summarize the most significant results and give ensuing recommendations. Additionally, we will discuss the facts that did not get enough attention and the points which need more consideration.

Compared to the current situation, all of the considered scenarios would enhance the greenhouse gas reduction. Methane can even be reduced with very simple methods.

Because of the diversity and scope of MSW, a waste management system solution needs to be as complex as the waste problem itself. In the different scenarios, a first step was made to integrate the individual treatments into an overall concept. Furthermore, we tried to consider the individual circumstances of the regions, however, the regions are a long way from having an organized waste management system and the data gap should be filled before jumping to conclusions and making definitive decisions. In particular, further investigations on the amount of waste and waste composition should be completed. Upgrading the current existing landfills with skilled staff, truck scales, daily covers, and various precautions would not just reduce emissions, but also help monitoring the data. What should also be taken into consideration is, that waste prevention is part of modern waste management and implementing a new WMS will increase public awareness.

Assuming the first step scenario will be reached in the year 2025 and our estimations about the amounts are close to the realistic values, the following recommendations from an environmental point of view can be made:

The main differences in the scenarios for D. region, are the amount of input into the MBT and the consumption of the waste due to the different amounts of separately collected recyclables and organic waste. After calculating the greenhouse gas emissions for the three versions, it became clear, that the scenario with the best results, with regards to the net emissions, is scenario 2B: full recycling + composting. Even though the “high tech” version avoids the most GHG in every scenario, it is not advisable from an economical viewpoint.

Two possible solutions were chosen to be more practical options. The first is the “low tech” MBT, which could, in the future, be upgraded with a sanitary landfill (less net emissions with a gas collection system). The second solution would be to have a partnership with the surrounding cities and regions to jointly build an MBT with higher capacities. Because more regions would have access to a high tech waste facility, this solution would have the advantage that more total emissions would be avoided. Additionally, the specific investment and operational costs of this solution would decrease with the higher throughputs. More investigations, such as, the collection logistics and the funding for the system are needed to decide on such a partnership.

Considering the current calculations with the small input in the D. region, we recommend to adapt the scenario with less technology and to introduce a system highly efficient in separate collection. Not included in the calculations are the emissions which will be released due to the waste transports. Those emissions will increase when more recyclables are collected separately. Also not included in the calculations is the reduced production of the fertilizer, which might be replaced with compost.

Due to the high throughputs in the Mogilev region, a higher potential for different variations is available, which is also expressed in the scenarios. Essentially, the Mogilev region is suitable for a “high tech” facility, especially considering that the incineration plant avoids much more GHG emissions than it releases. Unfortunately, the investment costs for such a plant are comparatively high. The best results will be achieved with the full energy recovery, however, precisely that scenario does not take ZUBR into account. It might be a possibility to upgrade ZUBR to an MBT, in order to include it in the future scenarios.

A compromise for the environmental protection and the economical benefit could be scenarios 1 and 2 with a “high tech” MBT. As discussed previously, there are many other options between the “low tech” and “high tech” version of the MBT. A facility with a high tech mechanical pre-treatment, manual sorting and tunnel rotting (like we described for the composting), could be a good alternative for a high tech facility in the Mogilev region. With a high quality of waste pre-treatment, a sanitary landfill without gas collection system might also be sufficient.

Different strategies of waste management concepts can achieve different goals. For that reason, it is necessary to define the goal to be achieve. The focus can be on the environmental protection, the circulation of the materials in most natural cycles or the energy recovery potential. In Germany, it is written in the law, which of those has priority. However, the MBT Kahlenberg also shows that there can be conflicts between legal regulations and economically viable solutions.

One clear solution for a waste management system does not exist, and finding the solution most suitable for individual scenarios is difficult. This thesis gives an overview of different facilities, discussing their advantages and disadvantages.

All in all, the following generalized final statements can be made for both case study regions:

- Further investigations on amounts and composition are necessary.
- These terms, amounts and composition, should be adopted in the facility designs (facilities built for higher capacities than the actual annual throughput can lead to higher overhead costs than were calculated).
- The gained experiences and calculations of the GHG balance show that every change, even if it is just an MBT with very low technology, will improve the protection of the environment immensely.
- The better the pre-treatment of the waste, the less technology is needed for the landfill.
- Less technology requires more efficiency in the selective waste collection.
- With higher throughputs, “high tech” facilities are more economical and do not require collecting the recyclables separately, so long as the MBT has a high efficiency in the mechanical treatment.
- The GHG calculations only included the facilities themselves and the material recovery, but not the further use of compost or emissions, which occur from transports and collection.
- The state of the art approach for organic waste treatment is a combination of anaerobic digestion and composting.
- “High tech” facilities are not a guarantee for optimal results; the operating management will always influence the outputs.
- The best results can only achieved with optimal operating conditions, especially when working with microorganisms.

References

Beckmann, M; Thomé-Komiensky, K.: Das Ersatzbrennstoffproblem – Aufkommen, Charakterisierung und Einsatz, Tagung Berlin November 2005, In: Ersatzbrennstoffe 5 - Herstellung und Verwertung

Bilitewski, B; Härdtle, G; Marek, K.: Abfallwirtschaft, 2. Auflage, Springer-Verlag, Berlin (1994), 635 S.

Bilitewski, B.; Härdtle, G.: Abfallwirtschaft – Handbuch für Praxis und Lehre, Springer-Verlag, Berlin (2013), 874 S.

Bockreis, A.; Müller, W.: Best Available Techniques (BAT) for Mechanical-Biological Waste Treatment Plants in: Thomé-Kozmiensky, K.; Thiel, S. (Eds.): Waste Management – Waste-to-Energy, Volume 4, TK Verlag Karl Thomé-Kozmiensky, Neuruppin (2014), 521 S.

Boer, E. den; Boer, J. den; Jager, J: Waste management planning and optimisation – Handbook for municipal waste prognosis and sustainability assessment of waste management systems, ibidem-Verlag, Stuttgart (2005), 273 S.

Bonnet, M.; Viertel, J. L.: Herstellung und Verwertung von Ersatzbrennstoffen unter besonderer Berücksichtigung des Werkstoffes PVC
URL: www.springer-vdi-verlag.de/libary/content/umwelt/.../ArtikelEBS-PVC_34047.pdf
Zugriff: 29.03.2017 – Stand: 2007

Bundesgütegemeinschaft Kompost e.V.: Vorstellung von Produktionsanlagen in Informationsdienst Humuswirtschaft & KomPost - Kompostwerk Mechernich (2003)
URL: https://www.kompost.de/fileadmin/docs/Archiv/Anlagenbeschreibungen/Mechernich-Mehren_3027_HuK_3-03.pdf
Zugriff: 21.04.2017 – Stand: 2003

Christensen, T:Solid Waste Technology and Management, John Wiley&Sons (2011), 1052 S.

DepV – Deponieverordnung/Landfill Ordinance: Verordnung über Deponien und Langzeitlager Hrsg: Bundesminesterium für Umwelt, Naturschutz und Reaktorsicherheit, Erlass, vom 27.04.2009

Dornack, C.: Lecture: Biologische Abfallbehandlung, Modul: Abfall- und Ressourcenwirtschaft, Technische Universität Dresden (2016)

Economopoulos, A: Planning Tools and Procedures for Rational Municipal Solid Waste Management, in: Waste to Energy – Oppertiunities and Challenges for Developing and Transition Economies, Karagiannidis, A; Springer-Verlag, London (2012), 370 S.

Evans, G: Biowaste and Biological Waste Treatment, James & James Ltd, London (2001)

Fricke, K; Müller, W.: Stabilisierung von Restmüll durch mechanisch-biologische Behandlung und Auswirkung auf die Deponierung – Endbericht: BMBF – Verbundvorhaben Biologische Vorbehandlung von zu deponierenden Abfällen
URL:*www.cleaner-production.de/fileadmin/assets/26407_-_Abschlussbericht.pdf*
Zugriff: 12.04.2017 – Stand: 1999

Hoeß, P; Ammon, J: Durchführung einer Hausmüllanalyse in der Stadt Wasserburg a. Inn Endbericht (2012)
URL: www.wasserburg.de/de/download/abfallwirtschaft_hausmuellanalyse.pdf
Zugriff: 29.03.2017 – Stand: 2012

IFAS – Ingenieurbüro für Abfallwirtschaft: Fachgutachten: Methanemessionen aus der Ablagerung von mechanisch-biologischen behandelten Abfällen” im Auftrag des Umweltbundesamt (2012)
URL: *www.ifas-hamburg.de/pdf/UBA-MBA-CH4-Emissionen_Bericht_IFAS.pdf*
Zugriff: 11.04.2017 – Stand: 27.04. 2012

Kern, M.: Strukturanalytische Untersuchungen und Bewertung schadstoffhaltiger Abfälle im Hausmüll, Dissertation (2006), 148 S.
URL: https://kobra.bibliothek.uni-kassel.de/bitstream/urn:nbn:de:hebis:34-200604038943/1/DISSERTATION_M.%20KERN_MAERZ_2006.pdf
Zugriff: 29.03.2017 – Stand: 2006

LUBW: Landesanstalt für Umwelt, Messung und Naturschutz Baden-Württemberg (2017)
URL: http://www4.lubw.baden-wuerttemberg.de/servlet/is/207233/
Zugriff: 10.04.2017 - Stand: 2017

Merten, M; Person, G; Schreiber, M: Moderne Abfallbehandlung - die MBA Kahlenberg (2006), S.65
URL: http://www.abfallwirtschaft-ortenaukreis.de/fileadmin/user_upload/MechanischBiologischeAbfallbehandlung/MBA_Artikel_und_ZAK_Verfahren.pdf
Zugriff: 20.04.2017 – Stand: 2006

Müller, W; Bockreis, A: Relevance, Targets and Technical Concepts of Mechanical-Biological Treatment in Various Countries. In: Waste-to-Resources, IV Internationale Tagung MBA & Sortierung, Cuvillier Verlag, Hannover (2011)

Person, G: Präsentation Eigenbetrieb Abfallwirtschaft Ortenaukreis –MBA Kahlenberg – Gewinnung von Energie und ROhstoffe aus Abfall (2012)
URL: http://www.abfallwirtschaft-orten-aukreis.de/fileadmin/user_upload/MechanischBiologischeAbfallbehandlung/02_2012_Juli_MBA_Praesentation_Korr_Person.pdf
Zugriff: 19.04.2017 – Stand: 2012

Ramke, H.-G.: Plausibilitätskontrollen in der Analytik von Zuordnungsparametern fester Siedlungsabfälle in: Fachgespräch Feststoffuntersuchung 2008 – Neue Entwicklungen in der Abfall- und Altlastenuntersuchung BEW-MUNLV-Seminar, BEW Bildungsstätte Essen, Ministerium für Umwelt und Naturschutz, Landwirtschaft und Verbraucherschutz des Landes NRW (2008)
URL: www.hs-owl.de/fb8/fachgebiete/abfallwirtschaft/.../Essen_2008_Beitrag_Internet.pdf
Zugriff: 29.03.2017 – Stand: 2008

Rettenberger, G: Demonstrationsanlage nach dem ZAK-Verfahren, wissenschaftliche Begleitung – Endbericht (2005)
URL: http://www4.lubw.baden-wuerttemberg.de/servlet/is/17038/projekt14_bericht.pdf?command= downloadContent&file name=projekt14_bericht.pdf
Zugriff: 20.04.2017 – Stand: Juli 2005

Sabery, F.: Modell zur Vorkalkulation von mechanisch-biologischen Restabfallbehandlungsanlagen zur Herstellung von Ersatzbrennstoffen, Dissertation (2003), 163 S.
URL: *https://depositonce.tu-berlin.de/bitstream/11303/1015/1/Dokument_25.pdf*
Zugriff: 29.03.2017 – Stand: 2003

Stief, K: Bau- und Betriebskosten der Abfalldeponie nach TA Siedlungsabfall, in: Tagungsunterlagen 1. Saarländische Abwasser- und Abfalltage, Berlin (1999)
URL: *www.deponie-stief.de/pdf/litstief_pdf/evs99kosten.pdf*
Zugriff: 11.04.2017 – Stand: Juni 1999

TASi: Technische Anleitung zur Verwertung, Behandlung und sonstigen Entsorgung von Siedlungsabfällen (Dritte allgemeine Verwaltungsvorschrift zum Abfallgesetz), Hrsg: Bundesministerium für Umwelt und Naturschutz, Kabinettsbeschluss, vom 21.04.1993
URL: http://www.bmub.bund.de/fileadmin/bmu-import/files/pdfs/allgemein/application/pdf/tasi_ges.pdf
Zugriff: 11.04.2017 – Stand: 21.04.1993

Thiel, S; Thomé-Kozmiensky, K: Mechanisch-biologische Abfallaufbereitung – Verfahrenskonzepte, Technik, Problme
URL:http://www.vivis.de/phocadownload/Download/2011_wm/2011_WM_CD_25_Thiel_TK.pdf
Zugriff: 17.04.2017 – Stand: 2011

Thomé-Kozmienzky, K.: Biologische Abfallbehandlung – Enzyklopädie der Kreislaufwirtschaft, EF-Verlag für Energie- und Umwelttechnik GmbH, Berlin (1995), 907 S.

Trautmann, N; Krasny, M: Online-Book: Composting in the Classroom (1997)
URL:https://ecommons.cornell.edu/bitstream/handle/1813/3338/CompostingInTheClassroom.pdf?sequence=1&isAllowed=y
Zugriff: 31.03.2017 – Stand: 1997

UBA - *Datenblatt: WT/S-01_MBT, Mechanisch-biologische Behandlung/Stabilisierung von Abfällen*
Datenblatt: WT/I-02_GCO, Thermische Abfallbehandlung – Rostfeuerung
URL: https://www.umweltbundesamt.de/sites/default/files/medien/377/dokumente/abfallaufbereitung_rostfeuerung_gco.pdf
Datenblatt: WD/D-03_SAL, Geordnete Siedlungsabfalldeponie für Hausmüll und hausmüllähnliche Gewerbeabfälle
URL:*http://www.umweltbundesamt.de/sites/default/files/medien/377/dokumente/abfalllagerung_hausmuelldeponie_sal.pdf*
Datenblatt: WT/I-04_FGC, Rauchgasreinigung
URL: https://www.umweltbundesamt.de/sites/default/files/medien/377/dokumente/abfallaufbereitung_rauchgasreinigung_fgc.pdf
Datenblatt: WT/R-05_COM, Biologische Abfallbehandlung – Bioabfallkompostierung
URL: https://www.umweltbundesamt.de/sites/default/files/medien/377/dokumente/abfallaufbereitung_kompost_com.pdf
Datenblatt: WT/R-06_ADI, Anaerobe Vergärung
URL: https://www.umweltbundesamt.de/sites/default/files/medien/377/dokumente/abfallaufbereitung_vergaerung_adi.pdf
Zugriff: April 2017 – August 2014

WaTra – Report about Case Study Region D.: Munisipal Solid Waste Management in the D. Rayon of N. Oblast (2017)

WaTra – Report about Case Study Region Mogilev: Overview waste management in post-Soviet states: Belarus, Russia and Kazakhstan. Waste management in case study region: Mogilev city and Mogilev District (2017)

WaTra – Waste Management in transition economies: Overview Report - Comparison of WM Systems in Western and Transition Economies (2017)

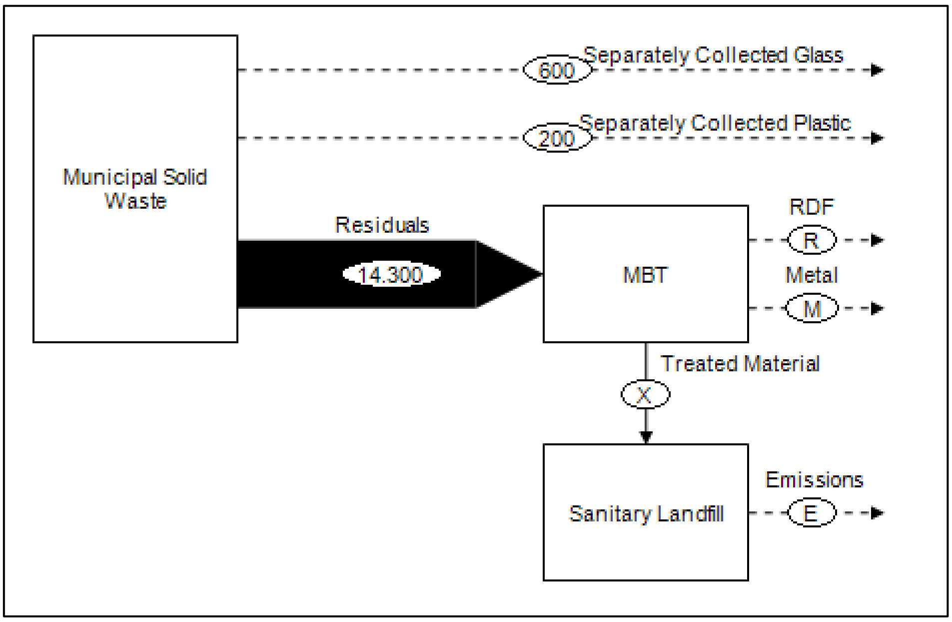
Witzenhausen-Institut für Umwelt, Abfall und Energie GmbH: Ökologisch sinnvolle Verwertung von Bioabfällen – Anregung für kommunale Entsorgungsträger, Hrg: Bundesminesterium für Umwelt, Naturschutz und Reaktorsicherheit (BMU); Umweltbundesamt (2012)
URL: https://www.umweltbundesamt.de/publikationen/oekologisch-sinnvolle-verwertung-von-bioabfaellen
Zugriff: 17.04.2017 – Stand: 2012

Eidesstattliche Erklärung

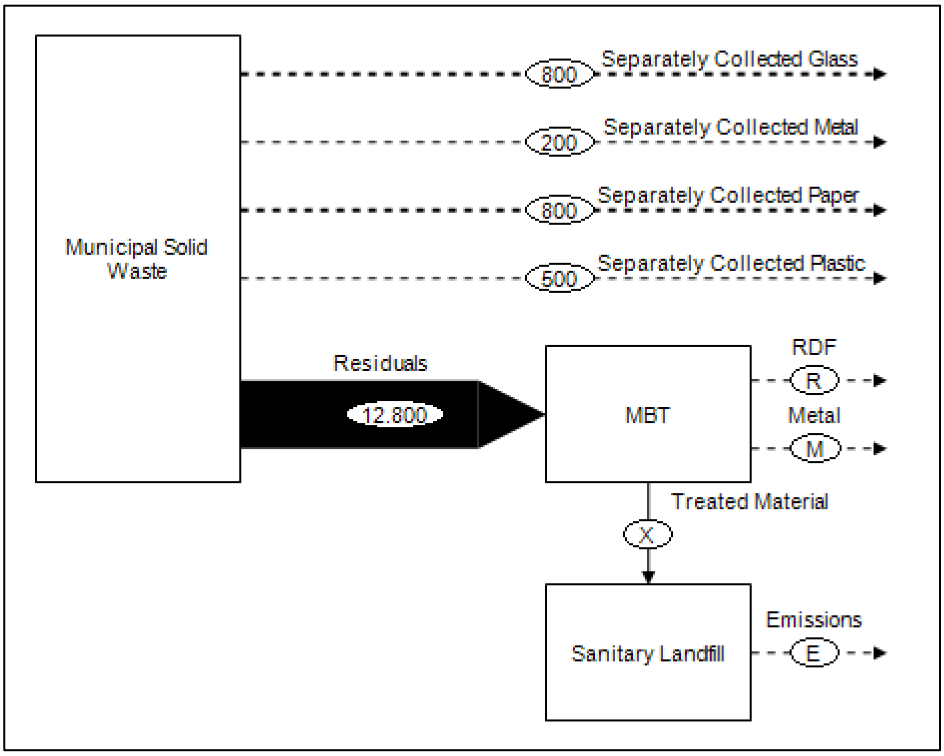
Hiermit erkläre ich an Eides statt, dass ich die vorliegende Arbeit selbstständig und ohne fremde Hilfe angefertigt habe. Sämtliche benutzten Informationsquellen sowie das Gedankengut Dritter wurden im Text als solche kenntlich gemacht und im Literaturverzeichnis angeführt. Die Arbeit wurde bisher nicht veröffentlicht und keiner Prüfungsbehörde vorgelegt.

Annex

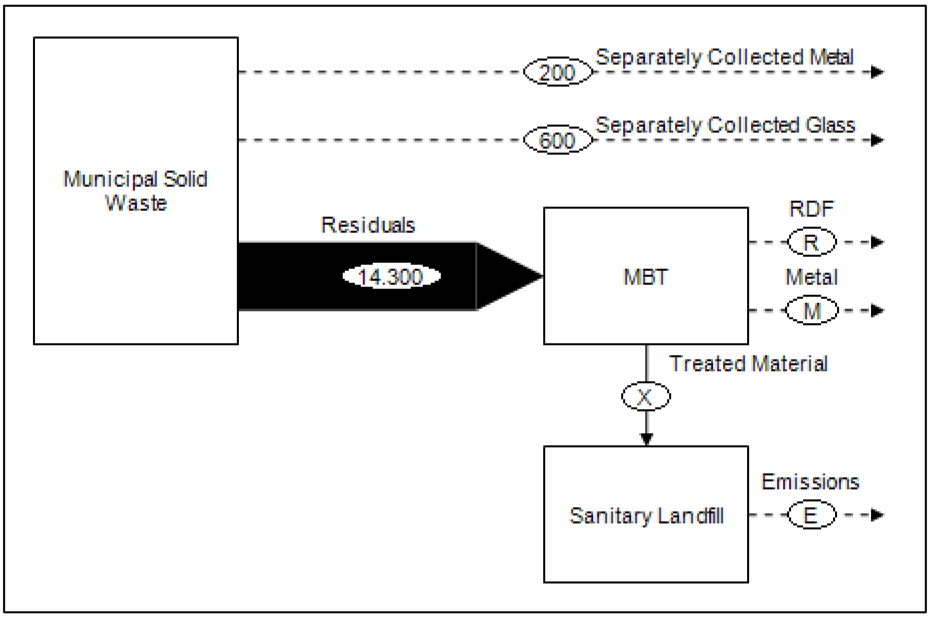
Annex-1: Flow charts of the scenarios for D. region



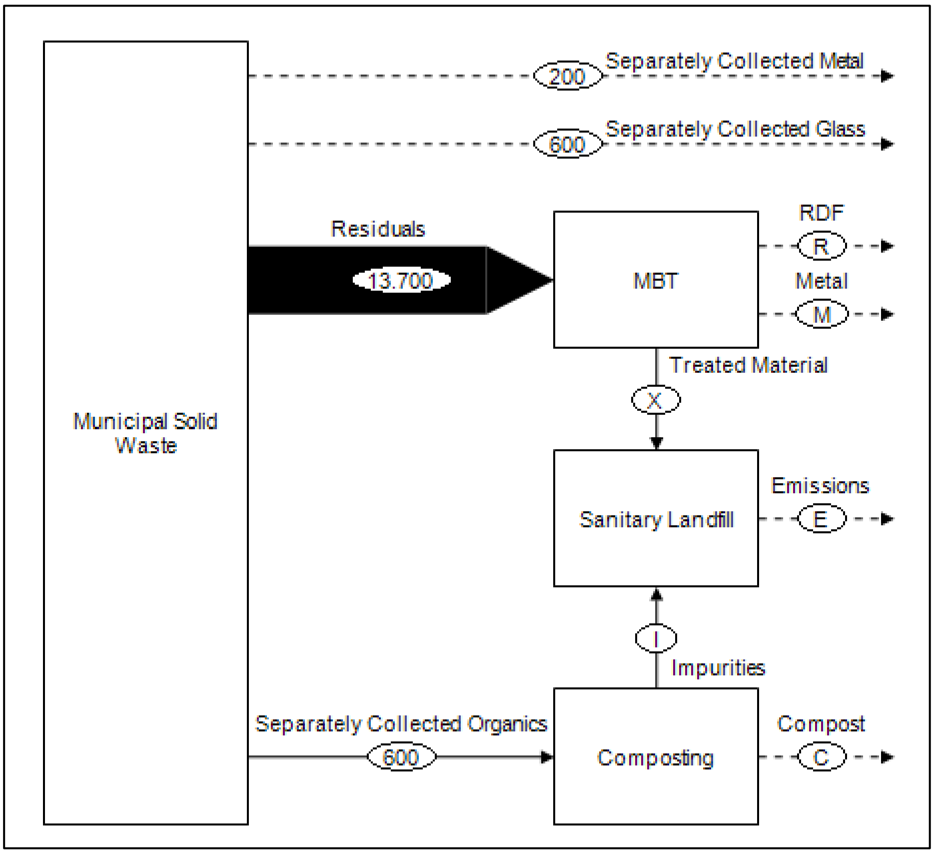
Anhang-1.1: Scenario 1A – Partly Recycling in [t/y]



Anhang-1.2: Scenario 2A – Full Recycling in [t/y]

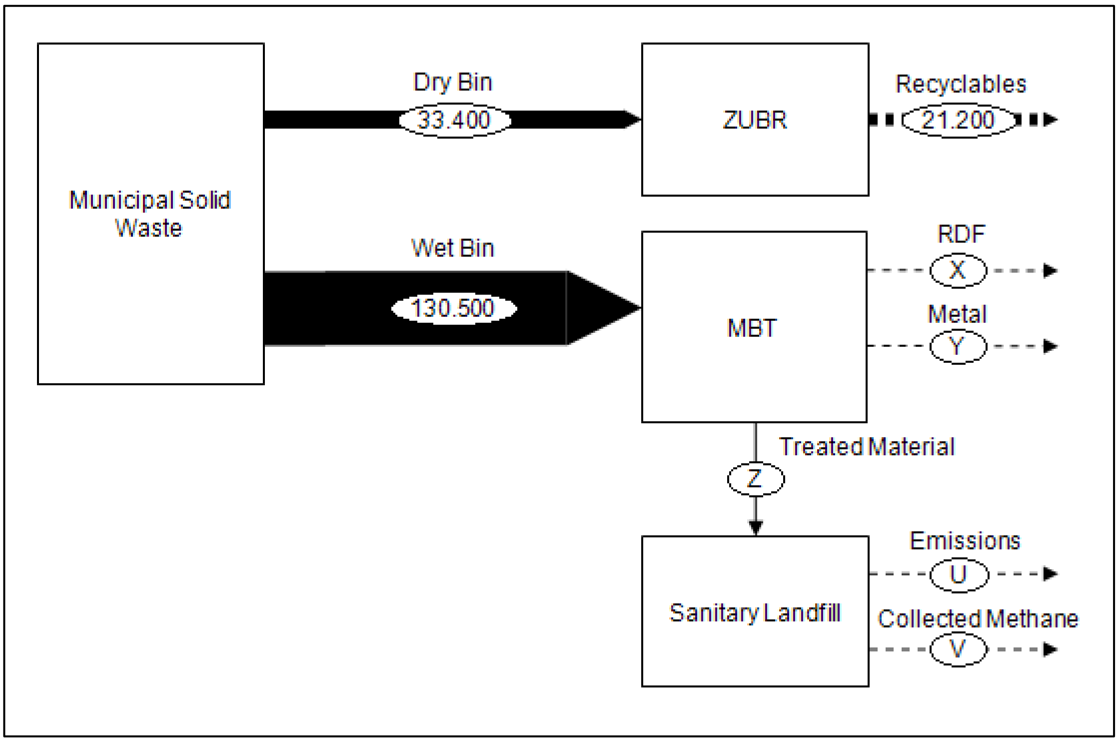


Anhang-1.3: Scenario 3A - RDF production in [t/y]

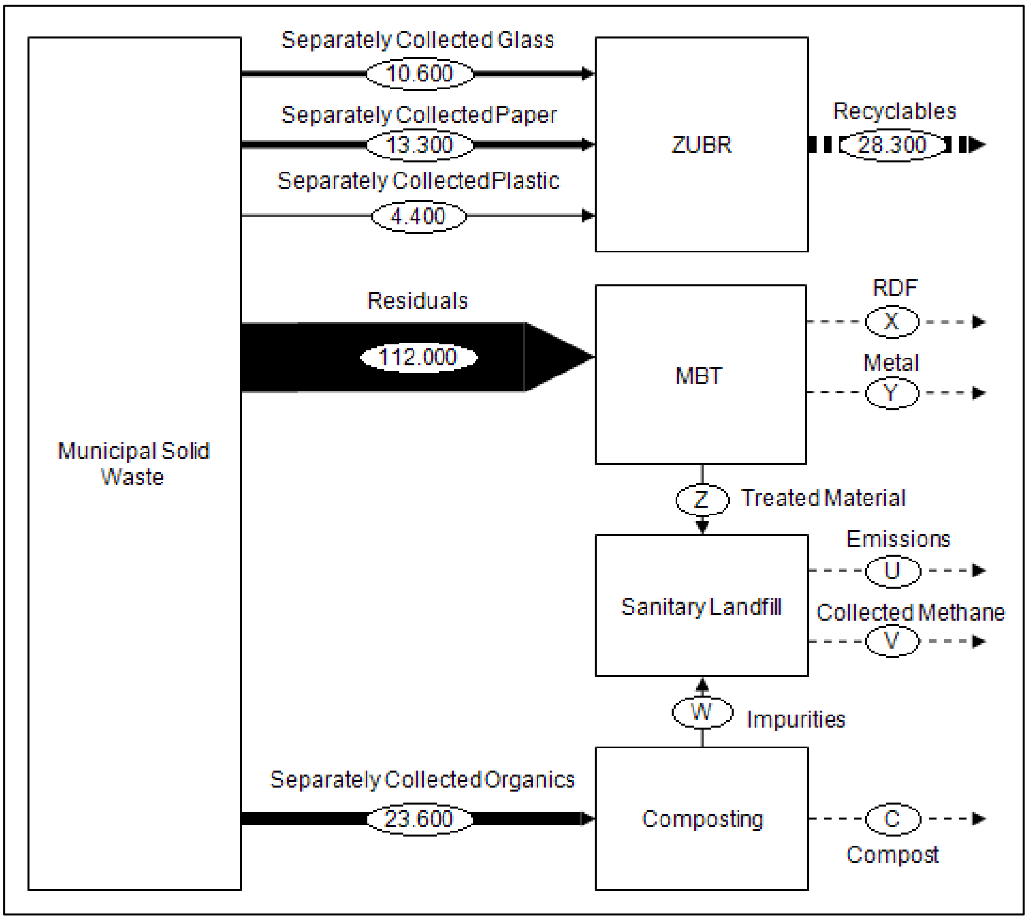


Anhang-1.4: Scneario 3B - RDF production + Composting in [t/y]

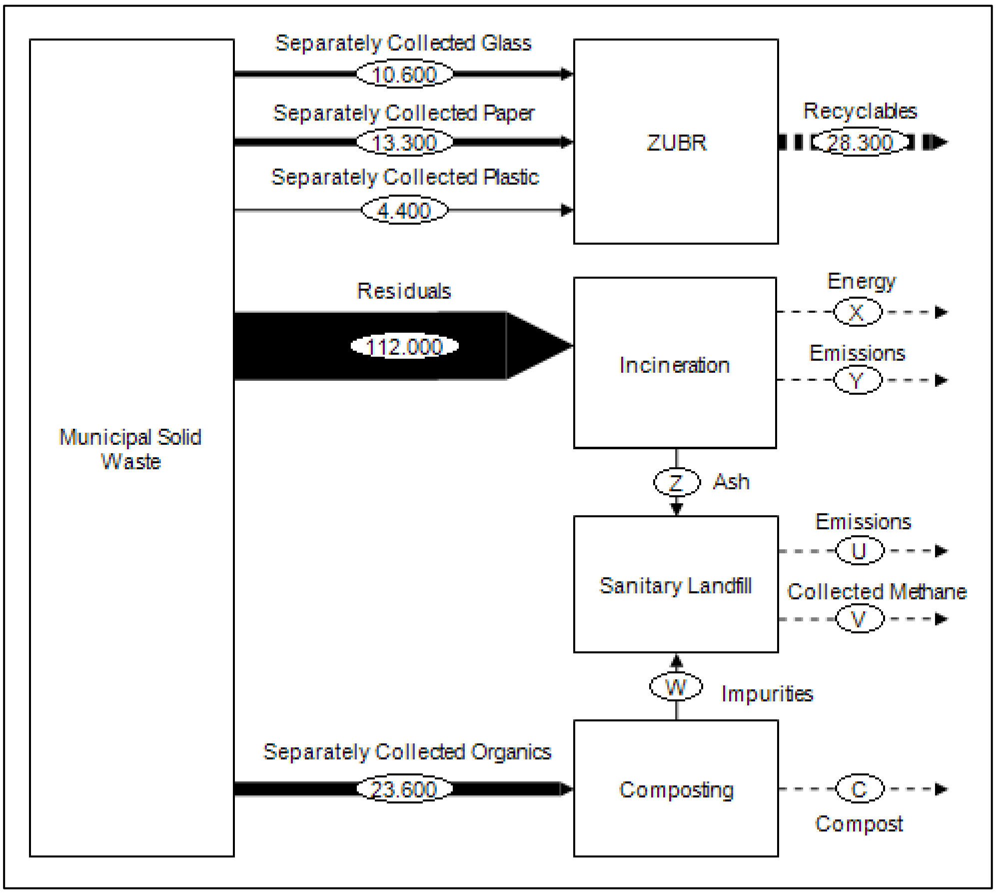
Annex-2: Flow charts of the scenarios Mogilev region



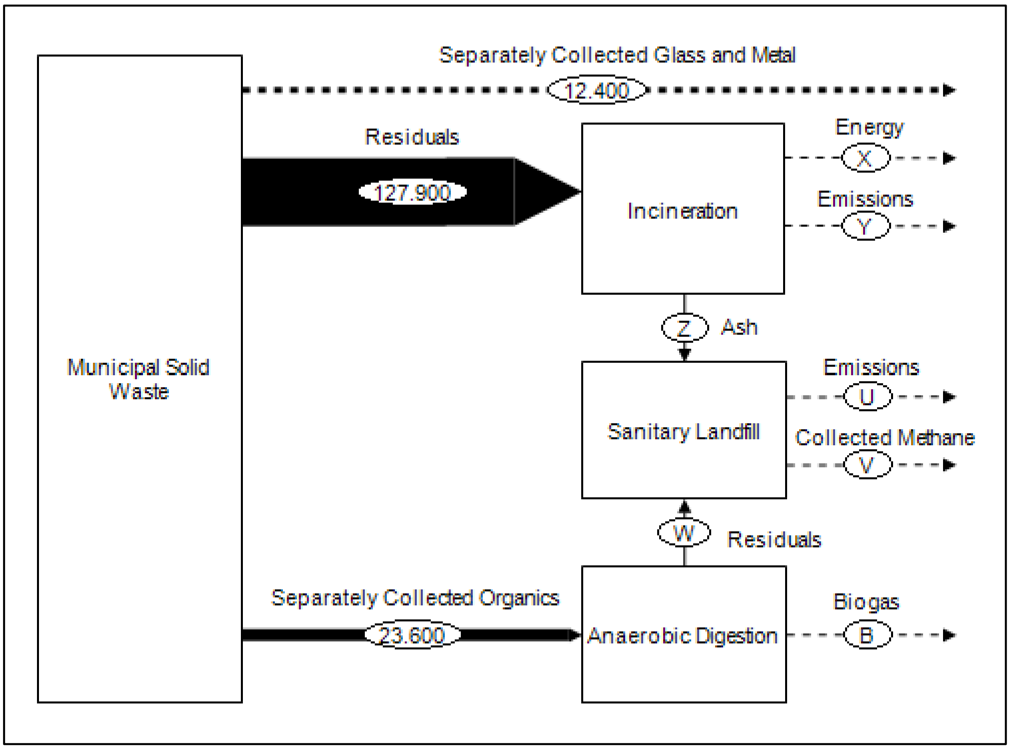
Annex-2.1: Scenario S1 in [t/y]



Annex-2.2: Scenario S2 in [t/y]



Annex-2.3: Scenario S3 in [t/y]



Annex-2.4: Scenario S4 in [t/y]

Annex-3: Contents of the Annex-CD

- PDF Document of this Project Thesis
- References
- Excel Table of Cost Calculations
- Excel Tables of Waste Composition
- Excel Tables of GHG Calculations