Waste Biomass Valor (2016) 7:175–191
DOI 10.1007/s12649-015-9428-6

ORIGINAL PAPER

The Relevance of Framework Conditions for Modelling GHG Emissions from rMSW Treatment Systems in EU

A. Clausen[1] · **T. Pretz**[1]

Received: 14 October 2014 / Accepted: 17 August 2015 / Published online: 21 August 2015

Abstract Apart from landfilling, there are two main technologies in order to treat residual municipal solid waste (rMSW): thermal treatment, particularly incineration with energy recovery, and mechanical biological treatment (MBT). It is generally accepted that both technologies show the potential to reduce the emission of GHGs when compared to landfilling. However, there is no consensus about whether incineration or MBT is the more climate friendly technology. Within the presented paper, the reasons for the ambivalent evaluation of GHG emissions from rMSW treatment are investigated. It is found that the contradicting positions regarding GHG emissions from rMSW treatment mainly result from (1) different modelling approaches and (2) varying framework conditions, which influence the performance of MSW treatment technologies. Based on these findings, a three step approach is developed to define requirements for a model, which allows a robust comparison of GHG emissions from two MBT technologies and one incineration approach taking into account varying backgrounds. The three step approach reveals numerous demands on material parameters that are driven by background conditions [(1) legal requirements (e.g. thresholds for emissions), (2) markets (e.g. metal separation), (3) the population and (4) climatic conditions]. Many of the background demands call for modifications/extensions of the examined technologies. Finally, a need for (1) a deeper understanding of biological treatment processes as well as (2) models of mechanical unit processes that are adjustable to different input materials are discovered as conditions for implementing robust comparison of MBT and incineration within different contexts.

Keywords Municipal solid waste (MSW) treatment · Incineration · Mechanical biological treatment (MBT) · Greenhouse gas (GHG) · Carbon footprint · Framework conditions · Background · Modelling

Introduction

The first driver from local dumping and open burning of municipal solid waste (MSW) towards technical MSW management was the prevention of odour nuisance and hazards for mankind. Since the 1960s, many countries introduced central sanitary landfilling in order to fulfil basic hygienic standards [1].

Then, back in the 1990s, there was a growing awareness of the climate impact of landfill gas emissions. Thus, when the global community of the United Nations Framework Convention on Climate Change set up the Kyoto Protocol [2] to reduce the worldwide greenhouse gas (GHG) emissions, one relevant field of concern was the waste management sector and the potential to reduce GHG emissions by treating waste prior to its landfilling.

It was within the Waste Framework Directive of the European Union (EU) [3], that the waste management hierarchy was legally established as a priority order when choosing a waste management system and it was this very directive, which called for life cycle assessment as the tool to be applied for evaluating the impact of waste management systems on human health and the environment. These demands on waste management (waste management hierarchy, LCA) yielded from the overall goal of the EU Waste Framework Directive ‘to protect the environment and

✉ A. Clausen
clausen@ifa.rwth-aachen.de

[1] Department of Processing and Recycling, RWTH, Aachen, Germany

human health by preventing or reducing the adverse impacts of the generation and management of waste…' [3, Art. 1].

The EU Landfill Directive [4] in turn was established to contribute to the compliance of the above mentioned goals of the EU Waste Framework Directive focusing on the reduction of negative impacts of landfill sides on human health and the environment. Thereby, Art. 1, 1 explicitly emphasizes the protection of the climate. In fact, the EU Landfill Directive demands from all EU member states to reduce the amount of biomass being disposed into landfills by 65 percent by mass compared to the year of 1995 (biomass reduction target). The aim of the biomass reduction target is to significantly reduce the emission of GHGs from landfill sites, as the highly potent GHG methane arises from landfilling of biodegradable waste ([4] Art. 5, 2). As a strategy to reach the biomass reduction target, the EU Landfill Directive generally prescribes the treatment of biodegradable waste prior to landfilling ([4] Art. 6, c) and specifically proposes the separate collection of waste according to the waste management hierarchy ([4] Art. 5, 1).

Following facts arise as a consequence of the described judicial regulations:

1. What may have been dealt with as MSW as a whole in the past—a mass flow, which, at the worst, a society simply got rid of in dump sites—requires a more detailed consideration nowadays, since legally binding targets are defined referring to different characteristics of substances/particles that are parts of this material flow.
2. As a result of implementing the targets laid down in the EU Waste Framework Directive and the EU Landfill Directive, numerous individual approaches of waste management systems including the introduction of separate collection for specific material groups have been established and are still established in different EU member states.
3. As separate collection efficiency can be assumed to never equal 100 %, each MSW management system has to handle a residual MSW fraction (rMSW), which—according to the EU Landfill Directive—has to be treated prior to landfilling.
4. According to EU legislation, the climate impact of waste treatment and hence the climate impact of rMSW treatment is to be kept as low as possible.

Figure 1 demonstrates the current situation of rMSW management in Europe. Thereby, the role of the population in terms of the rMSW quality is to be emphasized. First, the population generates a specific quality of MSW yielding from its specific consumption patterns. Secondly, the population defines the quality and quantity of the rMSW by the decision to direct MSW materials to a separate collection pathway (if available) or to dispose it as a part of rMSW.

As demonstrated above, the reduction of the climate impact of rMSW treatment is one objective of the EU Waste Framework Directive and the EU Landfill Directive.

In order to evaluate the contribution of different rMSW treatment technologies towards reaching these objectives, the climate impact of rMSW treatment technologies must be quantified. This is especially true when considering that several countries still struggle to comply with the EU Landfill Directive and decisions with respect to implementing an adequate waste management system are still to be made [5].

Apart from landfilling, there are two main technologies that are applied to treat rMSW, which are thermal treatment, particularly incineration with energy recovery, and mechanical biological treatment (MBT). It is generally accepted that both technologies show the potential to reduce emission of GHGs compared to landfilling. Both technologies stabilize the biodegradable part of the waste (incineration more complete than MBT), which leads to reduced methane emissions yielding from landfilling of these pretreated rMSW flows. In addition, both technologies allow recovering secondary raw materials, such as metals or plastics (MBT more complete than incineration) and energy (incineration more complete than MBT) from rMSW, which also contributes to reducing GHG emissions due to increased resource efficiency. Thus, both technologies may be applied in order to fulfil the EU Landfill Directive in general and its biomass reduction target in specific. But, when discussing the benefit for the climate, there is no consensus about whether incineration or MBT is the more preferable technology. However, as the climate impact of rMSW treatment is an issue to consider, when making related decisions (see the above mentioned legislation), it is the objective of this paper:

- To reveal the reasons for the lack of consensus about the climate impact of different rMSW treatment technologies by screening related literature, and, as a result thereof,
- To define the requirements on a model, that can help to assess the climate performance of the two main rMSW treatment technologies of waste incineration with energy recovery and MBT. Thereby, the focus lies on identifying the requirements for a robust comparison of the climate impact of MBT and incineration as a basis for developing a model. The issue of modelling itself and the quantification of the significance of different background conditions for the climate performance of rMSW treatment is beyond the scope of this paper and will be part of other (future) publications.

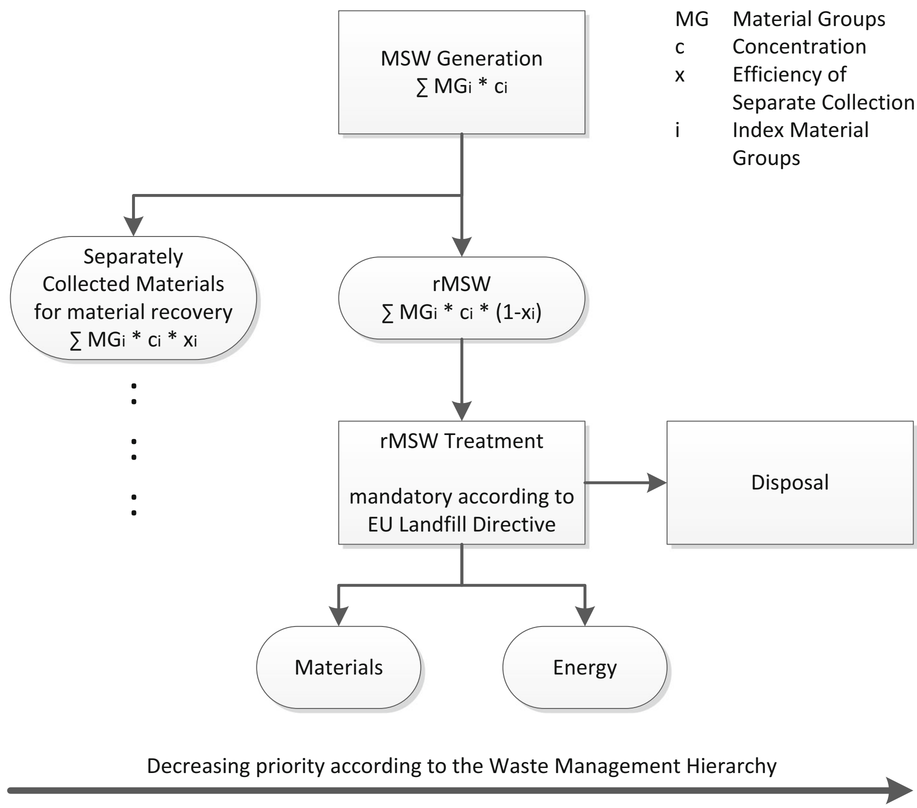

Fig. 1 Systematic overview of material flows in an rMSW management system according to the EU Waste Framework Directive

Literature Review

In order to identify potential reasons for the lack of a consensus regarding the climate performance of MBT and incineration, publications in the field of life cycle assessment (LCA) of rMSW treatment are elaborated and analysed. Thereby, one key issue is the conflict of two partly contradictory methodological demands, when modelling the GHG emissions from rMSW treatment:

- A comparative LCA demands methodological strictness with regard to modelling to ensure comparability [6].
- If the model shall help decision makers to estimate GHG emissions from different rMSW treatment options, there is a need to adapt the model to different technologies (foreground) and contexts (background), meaning that the model has to show a high level of flexibility in order to be applicable to different situations.

When screening publications in the field of GHG emissions from treating rMSW by incineration and MBT, it strikes (1) that there are only few scientific publications with regard to the climate impact of MBT technologies applying LCA methodologies, (2) that hardly any study directly compares MBT and incineration technologies and (3) that the results of existing studies with regard to the GHG emissions of MBT and/or incineration of rMSW show high variations and are sometimes even contradictory. This indicates that no general statement is possible in terms of evaluating, which of the two technologies shows better climate performance.

Montejo et al. [7] quote that within the last 25 years, about 180 MBT plants have been built in the EU. According to Steiner [8], there are two EU member states only—Denmark and Switzerland—, which neither do implement MBT at the moment, nor can be expected to focus on MBT in future waste management, since alternative rMSW treatment technologies—mostly incineration—already are implemented all over these countries. For all remaining EU member states, MBT either is part of the current rMSW management system yet or can be expected to be important as a future technology. But still, MBT is barely included when LCA studies compare different MSW treatment options. Laurent et al. [9] examined 222 LCA studies on solid waste treatment in general, including roughly 80 studies dealing with the management of ‘mixed waste from households’ (=rMSW). However, MBT is not a treatment technology considered within the clustering and assessment of the studies conducted by Laurent et al. [9]. Instead, landfilling and thermal treatment are subject of the examination solely. Apparently, no adequate scientific data is available for MBT. An overview of the 222 LCA studies that were part of the examination shows that just about four studies considered MBT at all.

Another study conducted by Cleary [10] that compares 20 LCA studies of MSW management systems did not consider MBT either. Instead, landfilling, thermal treatment and mixed treatment (a combination of landfilling, thermal treatment, biological treatment and/or recycling) were taken into account as treatment options. When screening the Ecoinvent 3.0 LCA database, the most common database used in solid waste LCA studies [11], it strikes that there are 31 processes available for the use of modelling MSW incineration, while no single MBT process is provided.

But why is MBT neglected compared to incineration when assessing GHG emissions from rMSW treatment even though MBT obviously is a technology of current and future relevance? [8].

There is wide agreement that two issues are responsible for the high fluctuations observed within the results of LCAs of rMSW management systems:

1. The methodological approaches, of which there exists a multitude for conducting an LCA of rMSW treatment, show a relevant effect on the related LCA study.
2. The context, which an rMSW treatment technology is implemented in, remarkably influences the technology's environmental performance (e.g. [6, 12]).

What is more, MBT does not equal MBT, as Montejo et al. [7] stated to the point. After describing the two main types of MBT technology, which are (1) the mechanical biological stabilization prior to landfilling (MBS) and (2) the mechanical biological drying for RDF production (MBD), the publication says that "Within this general classification, multiple variations can be found and it can be stated that probably there are no two identical plants." (Montejo, C. et al., p. 661) [7] This fact of technological variety combined with an input material known to be most heterogeneous, difficult to describe and typically showing a fluctuating composition result in challenging conditions for modelling MBT processes for life cycle inventory (LCI) calculations and may explain—at least in parts—why MBT is not documented in LCA, while incineration is.

As a result of the review of scientific publications, the author recognizes a general lack of methodologies to flexibly model the material flows for calculating an LCI of MBT processes. However, such flexible modelling tools are required, when decision makers in those EU member countries, which still undergo a process towards integrated waste management, aim to deliberate about whether MBT or incineration technology would be the more climate friendly solution within their waste management system.

Generally, it can be said that calculating the LCI is not the only challenge when conducting a LCA of rMSW treatment. Further examples are the accounting of biogenic carbon, allocation rules, selection of marginals, GHG emissions from landfills, time horizons, etc. However, these problems appear to be of more general relevance and not specific to MBT and thus cannot be identified to be the reason for a lack of MBT LCA studies.

Materials and Methods

As to the fact that there is the demand for a tool, by which the impact of different rMSW treatment technologies on the climate can be assessed and—in relation to such tool—the demand for methodological strictness and at the same time the option to adapt the background conditions, in the following, requirements are defined that need to be met by such tool.

Thereby, the focus lies on identifying the requirements on a model to determine material and energy flows of technical processes, which again allows determining the life cycle inventory (LCI) data necessary for conducting a carbon footprint study. Other methodological issues, e.g. considering the life cycle impact assessment (LCIA), are not part of this research. The requirements are defined in three steps, which can be summarized as follows:

Step 1: Basic Scenarios

- (a) Selection of rMSW treatment technologies (Scenarios)
- (b) Design of generic material/energy flow system

Step 2: CO_2-Balance

- (a) Determination of GHG emissions relevant for climate balance (CO_2-eq)
- (b) Detection of potential sources of GHG emissions
- (c) Detection of Background-related Modelling Parameters relevant for quantification of GHG emissions

Step 3: Influence of Background

- (a) Determination of detected Background-related Modelling Parameters potentially influenced by the background system
- (b) Determination of output flows potentially influenced by the background system
- (c) Impact on Scenarios

Step 1: Within Step 1 (a), the technologies, which shall be taken into account within the different Scenarios, are determined. These Scenarios encompass basic foreground technologies focusing on (1) the reduction of biomass being directed to landfilling and (2) the energy recovery coming along with the examined technologies. Material recovery is an integral part of state-of-the-art rMSW treatment and theoretically can be included in each Scenario (e.g. metals recovery). However, in order to keep the number of Scenarios limited and comparable, material recovery is not regarded within Step 1.

After selecting the rMSW treatment technologies to be investigated, a simplified mass and energy flow system of process chains is created (b), following the scheme presented in Fig. 2. The rMSW treatment technology itself is defined as the foreground system, while the background system encompasses auxiliary processes that take place in the technosphere but outside the rMSW treatment plant (MBT plant or MSW incinerator) and that are required for running the plant.

The flow system demands to be applicable generically to all Scenarios. The boundary of the system is chosen according to the prescriptions of ILCD Handbook. As the scope of the study generally addresses support for decision makers, consequential modelling and thus system expansion is applied (gate to grave/cradle approach) [6]. The system boundary in Fig. 2 and in Fig. 3 is chosen accordingly.

Step 2: Within Step 2, parameters relevant for quantifying the GHG emissions that result from the Step 1 Scenarios are examined in detail. In order to determine the parameters that generally have to be considered for modelling the GHG emissions, a backwards-check of the Background-related Modelling Parameters is necessary as described in the following.

(a) In order to determine the parameters that do have to be considered for modelling the foreground systems, first of all the potential output material flows that affect the climate (GHGs) must be identified. These are the material flows, which can be transformed into CO_2 equivalents (CO_2-eq) applying the global warming potential (GWP) and that are emitted to the atmosphere (see Fig. 2: OUTPUT atm). Within this work, GHGs that are subject to CO_2-accounting according to the Kyoto Protocol [2] and IPCC [12]

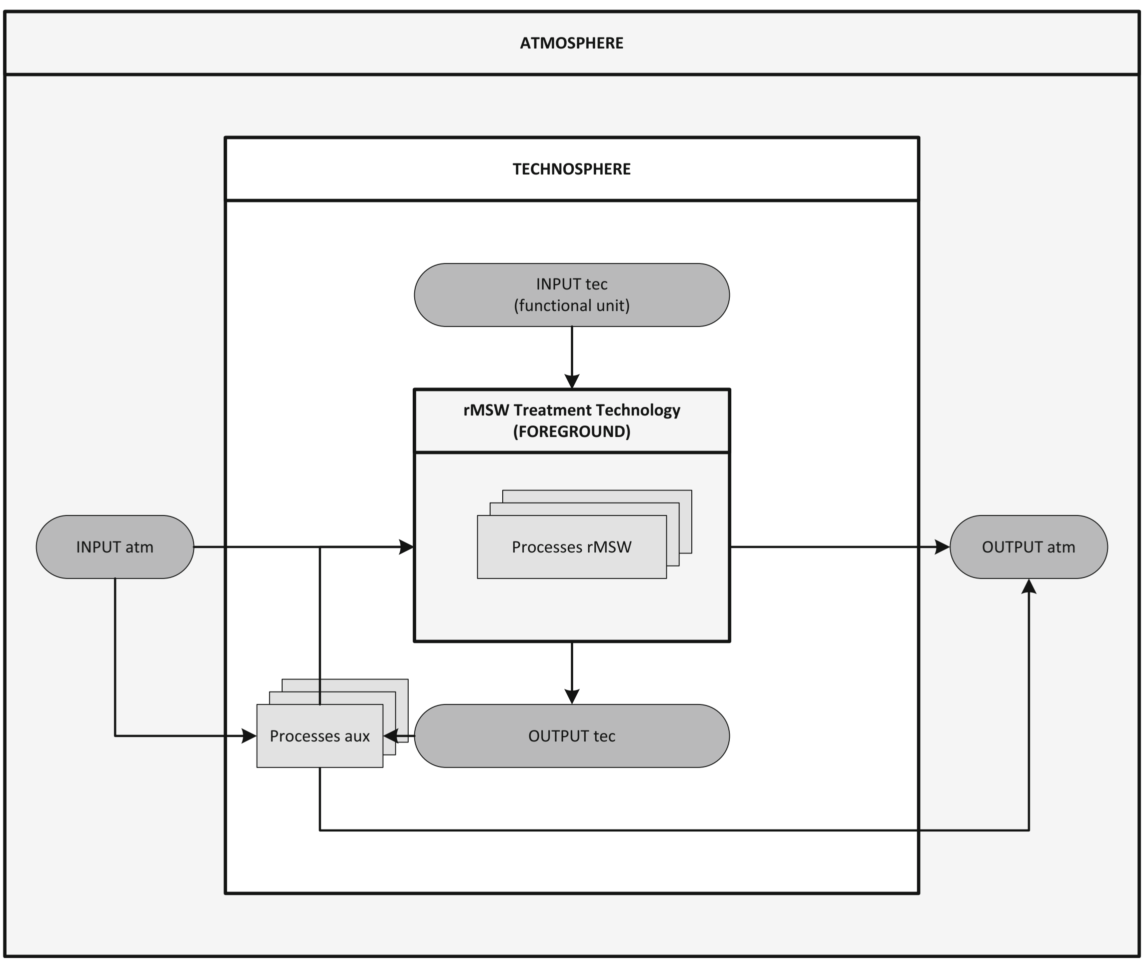

Fig. 2 System boundaries scheme that is to be applied for the generically flow chart within Step 1 b

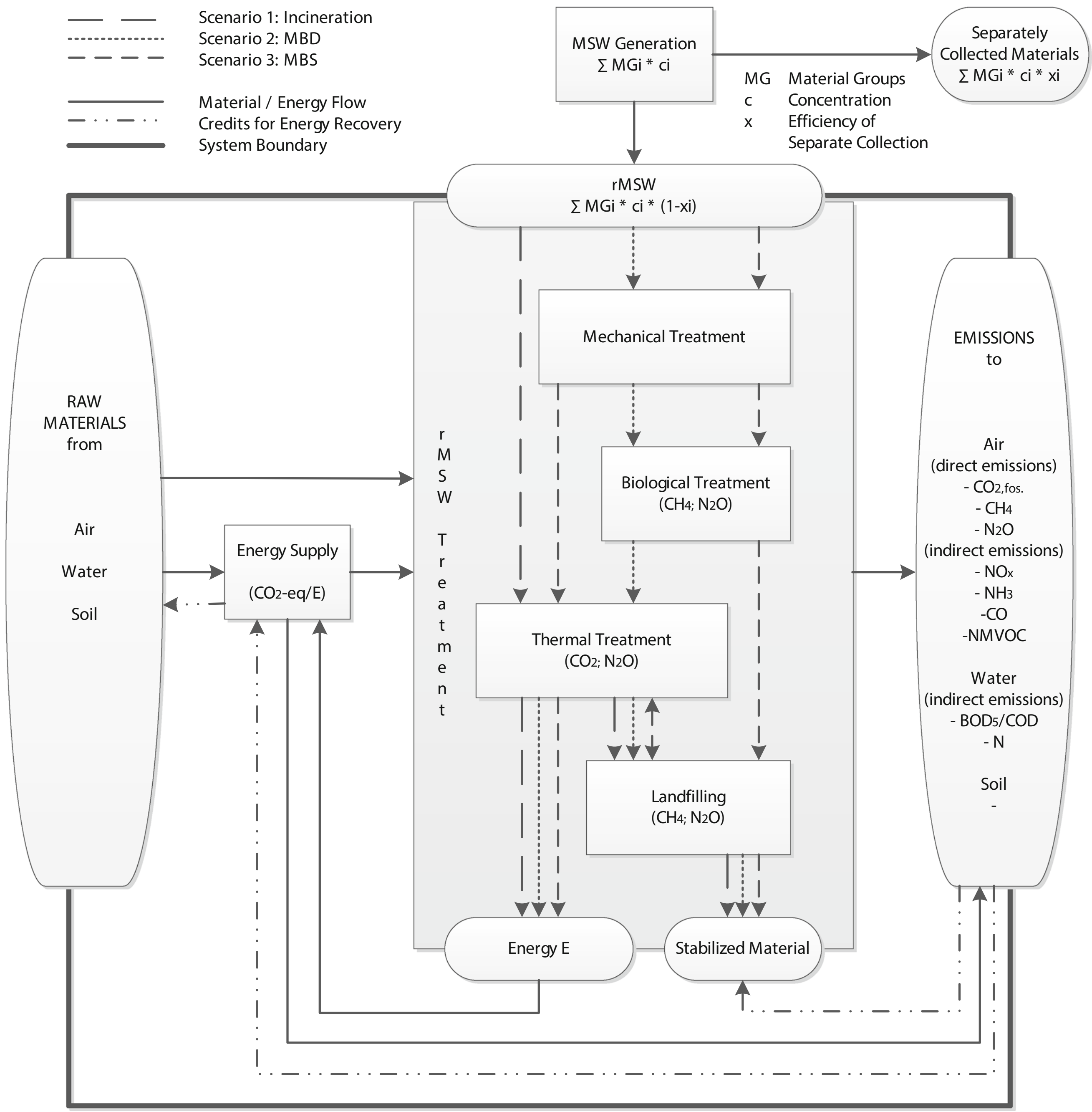

Fig. 3 Generic flow chart of the rMSW Treatment Scenarios investigated within the three step approach including potential sources of GHG emissions

are considered only. Correspondingly, CO_2 emissions yielding from biogenic MSW substances are not taken into account.

(b) In a second step, all process units (Fig. 2: Processes rMSW, Processes aux) are checked with regard to their potential of being a direct or indirect source (or sink) of one of the above mentioned GHGs. An indirect source of GHG emissions is an output material flow of a process unit, which shows the potential to be transformed into a GHG after being released to the atmosphere, e.g. waste water loaded with organic substances.

(c) Once that the sources of GHG emissions are defined, input and output material flows are examined with regard to the existence of mathematical dependencies that need to be known for modelling the GHG emissions. Thereby, those) parameters are identified, that (1) are required in order to quantify the GHG emissions and sinks arising from the Scenarios and that (2) at the same time are dependent on the background. That way, the link between the background system and the GHG emissions from rMSW treatment is investigated. The parameters identified in this step are hereinafter referred to as Background-related Modelling Parameters. Parameters related to process control and process efficiencies are not considered. These aspects are process specific and result from the foreground technology that is applied in a Scenario, d. The described procedure assures that the background conditions that potentially influence the GHG balance can be identified (see Step 3) and that these background conditions can be kept adaptable.

Step 3: Within Step 3, the potential influences of a background system on the modelling are determined. Based on these findings, parameters can be identified that need to be adjustable in a model in order to ensure that the model is applicable to different contexts. The needs for flexibility of the model are investigated as follows:

(a) First, the value of the Background-related Modelling Parameters defined in Step 2 (c) is checked with regard to its sensitivity towards the background system. Drivers that may influence the value of the Background-related Modelling Parameters are identified and the Background-related Modelling Parameters are assigned to the drivers that they are potentially influenced by.
(b) As a second step, the output material flows are checked with regard to their potential influence by the background system. Drivers that may influence them are detected. The parameters that are subject to potential direct influence by a driver are extracted and allocated to this driver. This step is required, as e.g. demands related to output material flows may trigger technological modifications, which again may impact the GHG emissions balance.
(c) In a last step, final basic demands on modelling yielding from the conducted examinations in Step 1, Step 2 and Step 3 (a) and (b) are gathered. Potential demands on settings and modifications of the investigated Scenarios or add-ons that may be driven by the background conditions and their drivers are highlighted.

Note: Specifying the impact of potential technological add-ons that are identified in Step 3 (c) is not part of this study and thus excluded when defining the basic demands on modelling.

Results

Step 1: Basic scenariosIn order to select Scenarios that are considered under the three step approach, a short overview of the technologies that are available for reducing the amount of landfilled biogenic rMSW is given.

Thermal treatment

- Thermal oxidization (Incineration)
- Other thermal treatment (e.g. pyrolysis, plasma arc technology)

Mechanical Biological Treatment (MBT)

- Mechanical biological stabilization (MBS)
    - Aerobic biological degradation
    - Anaerobic biological degradation
        - Wet processing
        - Dry processing
- Mechanical biological drying (MBD)
- Mechanical physical drying (MPD)

Other treatment (e.g. mechanical physical stabilization)

Incineration is the most common thermal treatment option with regards to rMSW. It applies thermal oxidization under excess air conditions in order to stabilize the organic carbon. Thereby, the biomass contained in rMSW is stabilized amongst other. State-of-the-art technology is the application of a grate stoker furnace, which can handle the heterogeneous characteristics of rMSW and its fluctuating composition most reliably. With regard to demands in terms of (1) flue gas cleaning, (2) the operation of the combustion process as well as (3) the treatment of the solid output flows from waste incineration, reference is made to the EU 'Integrated Pollution Prevention and Control Reference Document on the Best Available Techniques for Waste Incineration' (BREF WI) [13]. BREF WI provides an enhanced overview on the multitude of treatment options that are considered part of the best available technologies, which according to the EU Waste Framework Directive and the EU Industrial Emissions Directive must be considered, when managing MSW. Furhtermore, minimum efficiencies are defined with regard to energy recovery from waste incineration.

Apart from incineration, there are examples of other thermal treatment technologies being applied to treat rMSW, which are e.g. plasma arc gasification, a high temperature pyrolysis process. However, these technologies are of minor importance when evaluating the share of technologies that are applied for rMSW treatment. Hence, these technologies are not considered in any further detail within this study [14].

MBT was developed as an alternative to thermal treatment of rMSW, as incineration had and partly still has a bad reputation and low acceptance in society. The biological treatment is applied to avoid easily biodegradable substances from being landfilled. Due to homogenization, back-opening and concentration of bio-degradable substances, the mechanical treatment serves as a conditioning step for biological treatment. However, in contrast to incineration, different types of biological treatment are equally applied for MBT with different approaches to meeting the goal of the biomass reduction target. The different types of biological treatment can generally be classified into two major types: Mechanical biological stabilization (MBS) and mechanical biological drying (MBD) [15]. MBS aims for the decomposition of readily biodegradable substances as complete as possible. Thus, optimum conditions for degradation by biological activity are maintained during the process. MBS processes can be further divided into processes relying on a purely aerobic treatment on the one hand and processes applying a combination of anaerobic digestion for biogas production and aerobic stabilization of the remaining digestate on the other hand. MBD technology, in turn, uses the heat that is released due to the biological activity of aerobic bacteria in order to dry the rMSW material. That way, the heating value of the treated rMSW material is increased and thereby conditioned for its application as a residual derived fuel (RDF). [16] In analogy to BREF WI, the BREF WT (EU Integrated Pollution Prevention and Control Reference Document on the Best Available Techniques for the Waste Treatment Industries) [17] specifies (amongst other) BAT processes and technologies that can/shall be applied within MBT for biological treatment, flue gas cleaning and waste water treatment. Furthermore, limit values are defined for the volume of flue gas specific to the biologically treated amount of waste.

Apart from thermal treatment and mechanical biological treatment, other technologies exist, such as the mechanical physical stabilization. However, also these technologies are of minor importance when evaluating the share of technologies being applied in rMSW treatment and thus are not considered in any further detail within this study [15].

Even though recovery of material concentrates for material recycling is not part of Step 1, a short overview of correspondent technologies is given in order to complete the short survey of rMSW treatment technologies. Material recovery typically takes place by applying mechanical pre- and/or post-treatment. Numerous incineration and MBT systems include ferrous and non-ferrous metals separation units. Another important process in terms of incineration technologies is the treatment of bottom ash so that part of it can be recycled for the use as construction material. Subsequent to MBD systems, recovery of plastics concentrates is an option. Also mechanical enrichment of either specific qualities of fuels or inert materials is applied. Specifications of BAT and the manifold processes that can be applied for material recovery and refinery are provided in BREF WT [17]. BREF WI again claims minimum efficiencies for energy recovery from RDF [13].

(a) Considering said state-of-the-art technologies, within Step 1, one grate stoker furnace incineration approach (Scenario 1) and one example of each major MBT type—MBD in Scenario 2 and MBS in Scenario 3—are selected to be considered within a separate Scenario each. As a technological basis for the MBT processes, operating systems were chosen that are known to work reliably and efficiently and that are considered to be state-of-the-art. The biological process selected for the MBS Scenario is aerobic treatment, as anaerobic treatment is less often implemented and known to be a less robust technology or rather more sensitive to varying framework conditions [18]. The details of the processes selected for the Scenarios are the following:

Step 1 (a): Selection of rMSW Treatment Technologies

Scenario 1

Scenario 1 represents incineration applying a grate stoker furnace. Energy is recovered from the heat that is released during combustion. The bottom ash is cooled down by adding water, extracted from the system, stored for maturation/carbonation, which typically takes 1–3 months, and finally directed to landfills.

Scenario 2

Scenario 2 consists of a simple MBD process. After mechanical conditioning, the entire material is biologically dried by active aeration and thus converted into RDF for energy recovery by incineration. Apart from RDF, drainage water and condensate as well as waste air are output material flows of the process.

Scenario 3

Scenario 3, in contrast, represents a conventional MBS process. After homogenization of the rMSW, a coarse RDF fraction for energy recovery by incineration is generated by screening. The fine material is directed to aerobic biological treatment aiming to stabilize the easily biodegradable fraction of rMSW and thus condition it for subsequent environmentally sound landfilling. Air as well as water is supplied to the biological treatment process. By analogy with Scenario 2, drainage water and condensate as well as waste air are output material flows of the process. All Scenarios consume energy in the form of electricity, which is provided from the background system.

In general, processes that are not directly related to treating the rMSW but nevertheless potentially part of an MBT or incineration facility are not considered in Step 1. Examples are the waste air and waste water cleaning. The implementation of these process steps typically shows a strong dependency on the context and therefore will be subject of Step 3.

Step 1 (b): Design of Generic Material/Energy Flow System

The generic material and energy flow system yielding from the Scenarios presented in Step 1 (a) is demonstrated in Fig. 3. Apart from rMSW itself, energy and auxiliaries—both potentially derived from primary raw materials and thus related to emissions to the atmosphere—are supplied to the process chain. Auxiliaries, however, are neglected at the level of the presented examination. Each Scenario does not only consume, but also generate energy from combustion processes (rMSW/RDF incineration). This energy is supplied to the background system and hence may yield in emission credits. Apart from energy, all Scenarios generate a material flow for landfilling (stabilized material) representing a sink of the system.

Step 2: CO_2-Balance

Step 2 (a): Determination of GHG Emissions Relevant for Climate Balance (CO_2-eq)

The direct GHG emissions considered to be relevant for the GHG balance of the Scenarios are [12, p. 1.4]:

- Carbon dioxide (CO_2) from fossil origin
- Methane (CH_4)
- Nitrous oxide (N_2O)

Furthermore, indirect CH_4 and N_2O emissions may arise. Indirect CH_4 emissions yield from waste water, which is loaded with biogenic carbon that under anaerobic conditions is transformed into CH_4. According to the Intergovernmental Panel on Climate Change [12, p. 6.7], the material parameters relevant for the quantification of the CH_4 emission potential of waste water are the biochemical oxygen demand (BOD_5) and the chemical oxygen demand (COD). Indirect N_2O emissions in turn can be produced from NO_x or NH_3 that is released into atmosphere or from waste water containing nitrogen [12, p. 6.8]. Furthermore, non-methane volatile organic compounds (NMVOC) and carbon monoxide (CO) are indirect GHGs potentially emitted by waste treatment [12, p. 1.5].

Summarizing, following substances potentially are sources of indirect GHG emissions related to rMSW treatment:

- Mono-nitrogen oxides and nitric oxide (NO_x)
- Ammonia (NH_3)
- Carbon monoxide (CO)
- Non-methane volatile organic compounds (NMVOC)
- Chemical oxygen demand/biochemical oxygen demand (COD/BOD)
- Nitrogen in waste water (N)

All significant direct and indirect GHG emissions resulting from the investigated Scenarios are shown in Fig. 3 (EMISSIONS to Air/Water).

Step 2 (b): Detection of Potential Sources of Relevant GHG Emissions

Apart from mechanical treatment, each process shown in Fig. 3 potentially is a source of direct GHG emissions. In the following, the particular GHG emissions potentially arising from biological treatment, thermal treatment and landfilling are specified.

Mechanical Treatment

Mechanical treatment (homogenization and screening) can be considered to be no direct source of GHG emissions as no relevant chemical reactions do take place. For the sake of completeness, emissions, e.g. related to dust emissions or uncontrolled biological activity of the mechanically treated material are to be mentioned. However these emissions are neglected within this paper, as they are typically not reported as relevant sources of emissions when applying state-of-the-art technologies.

Biological Treatment (CH_4, N_2O, NO, NH_3, NMVOC, BOD, COD, N)

Biological treatment can yield in CH_4 and N_2O emissions as soon as anaerobic conditions appear during biological treatment [12, p. 4.4] or nitrification/denitrification takes place [12, p. 6.8]. Biodegradation of biomass also releases CO_2. However, as it is of biogenic origin, it is not taken into account as a climate relevant GHG emission [12, p. 1.5]. Indirect CH_4 and N_2O emissions may arise from the waste water discharged from biological treatment [12, p. 6.7]. Furthermore, there is a potential that indirect GHG emissions, such as NO, NH3 and NMVOC are formed [19].

Incineration (CO_2, N_2O, CH_4, NO_x, CO, NMVOC)

GHG emissions from incineration arise from oxidation of organic carbon to CO_2. Here again, CO_2 resulting from biogenic carbon is not taken into account as a climate relevant GHG, while CO_2 resulting from fossil carbon is. Further GHG emissions from incineration are N_2O (direct) and NO_x (indirect), which arise either from the nitrogen contained in the waste or from the nitrogen supplied to the process as a part of the combustion air. [12, p. 5.13] CH_4 potentially can be emitted from incineration plants, e.g. due to storage of the input material. However, state-of-the-art processing usually minimizes these emissions to a neglectable minimum, so that CH_4 emissions are not considered for incineration within this study [20, p. 460]. Also, indirect GHG emissions from CO and NMVOC do arise from incineration.

Landfilling (CH_4, N_2O, NO_x, CO, NMVOC, BOD, COD, N)

Landfilling leads to CH_4 emissions in case that degradable biomass is disposed under anaerobic conditions. CH_4 from landfilling is the most important GHG emission with regard to global waste management activities. CH_4 emissions may occur especially in Scenario 3, when biologically material is landfilled, which is not fully stabilized yet.

N_2O emissions from landfilling can be neglected as they do not occur in relevant portions [12, p. 3.6].

CO_2 emissions do occur from landfills, however are not taken into account, as they are from biogenic origin.

Leachate that may arise from landfilling can be categorized as waste water and hence follows the same rules as waste water discharged from biological treatment.

All treatment process steps can be expected to consume energy. GHG emissions related to the energy supply must be taken into account within the climate balance of the Scenarios. In reverse, emission credits must be considered for energy recovery from rMSW treatment to the extent that it replaces energy generation, which would have been related to GHG emissions. Also, sequestration of carbon from biogenic sources may take place in landfill sites, which must be accounted for.

The potential GHG emissions yielding from a process can be found within the process boxes in Fig. 3.

Step 2 (c): Detection of Background-Related Modelling Parameters Relevant for Quantification of Relevant GHG Emissions

In the final part of Step 2, the Background-related Modelling Parameters related to the background system, which must be supplied to a model in order to quantify the GHG emission flows and credits described in Step 2 (b), are identified.

Mechanical treatment itself is no direct source of GHG emissions. Nevertheless it must be modelled to the extent that is necessary to provide the information that is required for modelling the climate relevant, subsequent processes. For example: the output material flow of a homogenization process can be assumed to equal its input material flow. But still, further details have to be modelled, such as the particle size distribution, as these details impact e.g. the performance of subsequent biological drying. In order to make sure that all parameters relevant at any element of the process chain are modelled in sufficient detail from the beginning onwards, modelling criteria are examined starting with the last process and then back-checking stepwise.

Landfill Disposal

There are three major parameters that (1) are related to the background that landfilling takes place in and that (2) influence the CH_4 generation in landfill sites. First, there is the presence and quality of biodegradable substances; secondly, the moisture content of the material landfilled is important to determine the biological activity and third, the climatic conditions, in the following represented by temperature and humidity, play a role [12, p. 3.17/3.18]. In order to determine further GHG emissions potentially arising from landfilling, the carbon and nitrogen content are required as additional Background-related Modelling Parameters [19].

Energy recovery from landfill gas and related emissions/credits are not considered within the investigated Scenarios, as material with a low content of biodegradable substances is landfilled only due to the pre-treatment technologies. The dependencies of the transfer coefficients (TC) on the context are expressed in Eq. 1.

$$\mathrm{TC}_{\mathrm{landfilling}} = \mathrm{f}\left(\mathrm{c\,MG}_{\mathrm{biod}}, \mathrm{c\,MG}_{\mathrm{TOC/N}}, \mathrm{W}, \mathrm{T}/\varphi_{\mathrm{air}}\right) \qquad (1)$$

with c = concentration, MG = material groups, biod = biodegradability, TOC/N = total organic carbon and nitrogen content, W = moisture content, T/φ_{air} = temperature/humidity.

Thermal Treatment (Incineration)

When determining the GHG emissions yielding from combustion of rMSW or RDF, the fossil carbon content in the burnt material is the most important factor as fossil carbon is transformed to climate relevant CO_2 emissions by oxidisation. In order to determine the share of fossil carbon in the input material the moisture content, the total organic carbon (TOC) content and the origin of a material (biogenic/fossil) are required [12, p. 5.6].

N_2O emissions (direct and indirect) mainly depend on the technology implemented. The Background-related Modelling Parameter required for determination is the content of nitrogen in the input material [12, p. 5.13].

As incineration is a source of energy, which again must be considered for GHG emission accounting, the amount of effective energy must be determined too, when modelling incineration. Hence, the net calorific value of the dry matter is required as well. For modelling the material flows in general, the content of organic dry substance (ODS) must be known. The dependencies of the transfer coefficients of incineration and the context are summarized in Eq. 2:

$$TC_{combustion} = f\left(c\,MGC_{biog/foss}, c\,MG_{TOC/N}, NCV_{wf}, W, MG_{ODS}\right) \quad (2)$$

with c = concentration, MG = material groups, $C_{biog/foss}$ = ratio of biogenic and fossil carbon, NCV = net calorific value, wf = water free, W = moisture content, ODS = organic dry substance.

Biological Treatment

Similar to landfilling, the TCs of both processes, biological drying and biological stabilization, significantly depend on the share and quality of biodegradable substances and the moisture content of the material. Furthermore, the temperature and the aeration are mentioned as relevant parameters when aiming to determine the GHG emissions (CH_4 and N_2O) resulting from biological treatment [12, p. 4.6]. Research conducted at the Department of Processing and Recycling revealed crucial dependencies of biological processes on the particle size distribution of the material treated [21] as well as the temperature of the air supplied to the process [EU LIFE + Project LIVE11_ENV/DE/343 Material Advanced Recovery Sustainable Systems] and the relative humidity of the air. Both, temperature and humidity of the air supplied to the process, determine the water absorption capacity of the air and, hence, the drying effect. For indirect GHG emissions, again information about the TOC and nitrogen content of the input material are crucial [19].

The parameters influencing the GHG emissions of biological treatment are gathered in Eq. 3.

$$TC_{biological\ treatment} = f\left(c\,MG_{biod}, c\,MG_{TOC/N}, PSD, W, T_{air\,in}, \varphi_{air\,in}\right) \quad (3)$$

with c = concentration, MG = material groups, biod = biodegradability, TOC/N = nitrogen and total organic carbon, PSD = particle size distribution, W = moisture content, $T_{air\ in}$ = temperature air in, $\varphi_{air\ in}$ = relative humidity air in.

Mechanical Treatment

For both mechanical treatment processes, homogenization and screening, the particle size distribution is the most important characteristic that influences or is influenced by the process. During homogenization, the particle size distribution typically shifts towards a higher share of fine particles, whereas screening performance and material flow splitting is substantially influenced by the particle size distribution of the input material. Therefore, material groups showing different particle size distributions behaviour have to be modelled separately.

Another parameter, relevant in particular for modelling the screening process, is the moisture content [22].

The transfer coefficients (TC) of both processes can be described as a function according to Eq. 4.

$$TC_{homogenisation/screening} = f(c\,MG_{PSD}; W) \quad (4)$$

with c = concentration, MG = material groups, PSD = particle size distribution, W = moisture content.

Figure 4 gives an overview of all Background-related Modelling Parameters that were identified in Step 2 (c) to be relevant for modelling background impacts on the GHG emissions on any of the processes applied in the investigated Scenarios. Furthermore, the Background-related Modelling Parameters are assigned to the input flow that they depend on. In general, each process unit of the technologies consumes energy. To keep the flow chart as simple as possible, the energy consumed by the processes is not included specifically for each process but only for the foreground of rMSW treatment as a whole in Fig. 4. The same is applied for the GHG emissions. As in Fig. 3, the parameters to be determined for counting the GHG emissions are shown with the related output flows.

Generally, the Background-related Modelling Parameters can be assigned to two categories, (1) those, who are related to the composition of the rMSW input material and hence require a differentiation of the composition according to material groups, and (2) those, who are related to auxiliary materials, such as air and energy supplied to the process. With regard to the waste composition it must be considered that MSW compositions typically are analysed and reported according to material groups such as food waste, paper, plastics, metals, glass… (see e.g. IPCC default values for MSW composition in Europe [12, Vol 5, Ch 2]). In order to provide the Background-related Modelling Parameters that are shown in Fig. 4 and that are identified to be required for robust modelling of GHG emissions from MSW treatment, the material groups that are used to describe the composition of rMSW must be specified according to the Fig. 4 parameters.

Step 3: Influence of Background

Step 3 (a): Determination of Detected Background-Related Modelling Parameters Potentially Influenced by the Background System

The results of Step 3 (a) are gathered in Table 1, where the rows show the potentially influenced Background-related

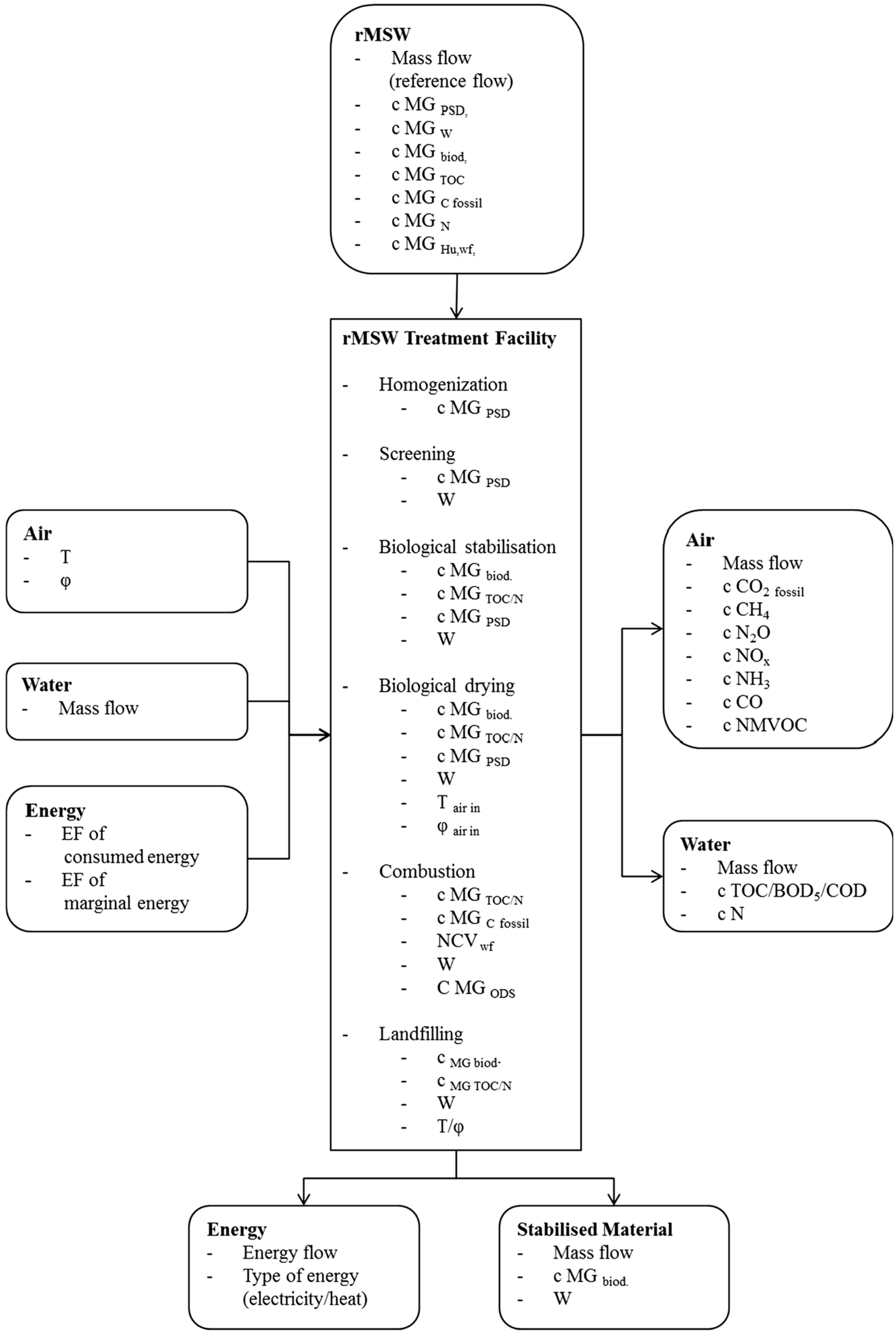

Fig. 4 Overview of Background-related Modelling Parameters and process parameters relevant for modelling of the Scenarios Abbreviations: *c* concentration, *MG* material groups, *PSD* particle size distribution, *W* moisture content, *biod.* biodegradability, *T* temperature, *φ* relative humidity, *TOC* total organic carbon, *BOD5* biochemical oxygen demand, *COD* chemical oxygen demand, *EF* emission factor, *C* carbon, *ODS* organic dry substance, *NCV wf* net calorific value moisture free

Modelling Parameters related to their input flows. The columns represent the drivers, which the Background-related Modelling Parameter may be directly influenced by. In total, four drivers of direct influence are identified, which are (1) law, (2) markets, (3) population and (4) climate. For the rMSW related Background-related Modelling Parameters (composition and amount), all four drivers are relevant:

1. Laws can influence the composition and amount of rMSW by bans of materials from the market, prescriptions of separate collection of certain valuable or

Table 1 Overview of drivers influencing input flows that are relevant for determination of GHG emissions from rMSW treatment

Input flow	Drivers			
	Law	Market	Population	Climate
rMSW	Composition [3, 28] amount [3, 28]	Composition, amount	Composition, amount	Composition, amount
Energy	Energy mix [24, 25]	Energy mix [24]	–	–
Air	–	–	–	Temperature, humidity
Water	–	Limited water supply	–	–

hazardous material flows and by incentives (e.g. fees or deposits) related to waste management.

2. The market is the second important driver, as e.g. demand for secondary raw materials directly impacts recycling activities within waste management systems.
3. The population and its needs are another driver, as they are the source of rMSW generation on the one hand and represent the link between waste generation and waste management on the other hand.
4. The last important driver identified for the composition and amount of rMSW is the climate, which influences the behaviour and consumption patterns of a society and thus the waste generation (example: seasonal fluctuations of waste composition [23]). Furthermore, the climate directly impacts biological processes taking place in waste materials during the period of waste generation and waste treatment.

The emission factor of the second input flow, the energy supplied to the system, mainly depends on two drivers: (1) laws (e.g. incentives for renewable energies, prohibition of nuclear energy… [24, 25]) and (2) markets (e.g. availability of energy feedstocks/infrastructure), whereas the temperature and the humidity of the air supplied, the third input flow to the process, directly are driven by the climate. In case of a background, where water supply is limited, markets may also influence this fourth input flow.

A detailed explanation with regard to the questions of how the parameters shown in Table 1 were obtained and what exactly their influences on modelling are requires specific descriptions of all relevant legislative texts as well as the mechanisms of interaction between markets and technological applications. As these issues are beyond the scope of this paper, they will be matter of further, separate publications (e.g. [26].

Step 3 (b): Determination of Output Flows Potentially Influenced by the Background System

The second part of Step 3 is more complex to cover than the first. The background system turns out to show a massive impact on climate performance with regard to its influence on the output flows of a waste treatment system. A multitude of laws is identified to put demands on the different potential output material flows. As a result, the Scenarios as described in Step 1 (a) need to be operated in a specific mode that can meet the requirements or even could not be implemented without adding further technological steps. Air cleaning is just one example out of many. Markets show a similar influence on the implemented technology, as the value of potential product flows and marketing strategies also impact the operation and the assembly of a rMSW treatment technology and the add-ons e.g. for material recovery.

Table 2 presents a selection of parameters (1) that are related to a middling or output flow of the investigated Scenarios, (2) that potentially influence the mode of operation or assembly of the technologies implemented in the Scenarios and (3) that hence influence theclimate performance as well.

Due to the complexity of the judicial and economic situation with regard to rMSW treatment output flows and the limited scope of this publication, selected examples can be shown only in Table 2. Nevertheless, the parameters shown in Table 2 demonstrate the variety of laws in this field and represent the major triggers of relevant developments in the field of rMSW treatment. For a comprehensive overview of this issue, reference is made to [26].

The material flow RDF is—amongst others—subject to legal and economic demands on its fuel parameters (e.g. German 'criterion on NCV for waste incineration). Furthermore statutory quotas with regard to recovery rates may influence the mass flow and quality of RDF produced.

Material to be landfilled needs to fulfil the demands set down in the EU Landfill Directive. The implementation of the EU Landfill Directive into German national law e.g. puts thresholds on the TOC content, the ash content and the calorific value, to mention some examples. The amount and quality of rMSW being landfilled also depends on pure market issues (e.g. gate fees for landfill disposal) and legal incentives influencing the market conditions such as the landfill tax in Great Britain [27].

According to German law, bottom ash from waste incineration cannot simply be landfilled, but must be

Table 2 Overview of drivers influencing middling and/or output flows that are relevant for determination of GHG emissions from rMSW treatment

Middling/output flow	Drivers	
	Law	Market
RDF	Mass flow and quality [4, 28, 29], $H_{u\ wet}$	Fuel parameters (e.g. W, ash content, C, S, O, H, N, Cl, NCV, heavy metals, PSD, $C_{foss./biog.}$)
Landfill material	TOC [2, 30], H [2, 30], ash content [30], heavy metals, leaching parameters, AT_4 [30], GB_{21} [30]	Amount and quality [27]
Bottom ash	Carbonation [31], PSD [31], Fe metals separation [31]	PSD, composition
Energy	Increased energy recovery [3, 28]	Type and amount of energy recovery
Air	CO_2 [2], TOC [32], TC [31], N_2O [32], dust [31, 32], HCl [31], HF [31], SO_2 [31], NO_2 [31], HG [31], CO [31], NH_3 [31], dioxins/furans [29]	–
Water	TSS [29], COD [33], BOD_5 [33], NH_4N [33], N_{ges} [33], P_{ges} [33], heavy metals [29, 33]	–
Secondary raw materials concentrates	Increased sec. raw materials recovery [3, 28, 30]	Mass flow, amount and purity of sec. raw materials concentrates

subject to metal recovery. Furthermore carbonation (a sink of CO_2 from the atmosphere, which is not considered within Scenario 1 yet) must take place prior to final recycling or disposal of bottom ash. Recycling activities with regard to bottom ash are mainly driven by the markets for construction materials and influence the GHG emissions from bottom ash due to increased resource efficiency by replacing e.g. primary construction materials.

Energy recovery is one demand on waste management that is included in the EU Waste Framework Directive and further specified e.g. in German national law [28]. Also carbon accounting plays a role for the energy recovered, as the option to recover climate neutral biomass fuel from rMSW may be an incentive for technological add-ons to the technologies described in the Scenarios.

One crucial aspect with regard to the climate performance of rMSW treatment (in a positive and negative way) are the legal requirements on air emissions from rMSW treatment. Some examples for statutory thresholds put on exhaust air flows from rMSW treatment in Germany, which require different applications of air cleaning, are the parameters TOC, NO_2, NH_3, SO_2 and dioxins and furans (EU law).

Similar to the exhaust air, there are thresholds for different parameters of waste water that need to be met to allow discharge, as e.g. BOD/COD, the total nitrogen and the total phosphorus content.

The last material flow is the flow of secondary raw materials, which is (1) generally demanded by EU law and specified in more detail e.g. in German national law, (2) driven by the increasingly strained raw materials markets and (3) already mentioned with regard to demands on bottom ash treatment. For the sake of simplicity, this material flow is not included into the Scenarios yet. Recovering secondary raw materials often does not only require technological add-ons to the described Scenarios but separate treatment in a specific material recovery plant. These plants itself may be equally complex with regard to modelling when compared to the investigated waste treatment Scenarios. However, the principles of modelling and the influence of the background system follow the same (mathematic) rules as the one presented in Step 2 and Step 3.

The drivers presented in Table 2 do not cover all relevant drivers, as—in support of a clear arrangement of the table—drivers that do not have a unique influence on parameters are not listed. For example: Decision makers have an impact on different material flows, as they decide about if a rMSW treatment technology is implemented and how. However, all parameters identified to be relevant for decision makers were already found to be covered by the parameters influenced by markets and laws.

Step 3 (c): Impact on Scenarios

Due to the fact that most of the parameters mentioned in Table 2 can be influenced by a number of different treatment options, it is beyond the scale of this publication, to mention all thinkable combinations of add-on technologies that may be implemented driven by a certain background system. For Scenario 1 (Incineration), the 'Reference Document on the Best Available Techniques for Waste Incineration' [13] provides an enhanced overview on the multitude of treatment options with regard to the output material flows of an incineration plant. With regard to cleaning and refinery steps for output material flows of Scenario 2 (MBD) and Scenario 3 (MBS), the 'Merkblatt

DWA-M 388' [16] gives an overview on state-of-the-art treatment options and available technological components.

Summing up, it can be said that processes from all fields of process technology are represented within possible add-on technologies for the Scenarios. The following examples show that in the field of waste air cleaning alone, applications from all fields of process technology are available, which correspondently require individual modelling approaches. Waste air from MBS processes e.g. can be cleaned using a biofilter (biological) and/or reverse thermal oxidation step (thermal). For dedusting of flue gasses from incineration processes, bag filters (mechanical) and electric filters (physical) are available and one option to reduce NO_x emissions is the process of selective catalytic reduction (chemical).

In order to include air and waste water cleaning steps as modules for the Scenarios, the three step approach has to be applied to the cleaning processes in question. Thereby, the level of detail has to be kept (1) as low as possible, to keep the model handable, and (2) as high as necessary to not neglect relevant GHG emission flows.

Secondary raw materials recovery from solid material flows often takes place in separate material recovery facilities and thus is part of the background system. Thereby, solid material flows are typically supplied to a chain of different mechanical treatment steps for pre-conditioning prior to recycling itself. Similar to MBT plants, hardly any material recovery facilities equals another. Nevertheless, different research projects conducted at the Department of Processing and Recycling, RWTH Aachen showed that for example different state-of-the-art plants for plastics recovery from rMSW achieve comparable recovery efficiencies ('Post-consumer packaging recycling' (TIFN SD001), Study: 'Vollständige ökoeffiziente Verwertung von Siedlungsabfällen aus der Region Trier' (RegAb, MBT Mertesdorf, Trier 2010)). Simple transfer coefficients should therefore be applied for modelling such facilities.

Discussion and Conclusions

Creating a model that allows determining the GHG emissions from incineration and particularly MBT technologies for rMSW treatment under consideration of varying background conditions constitutes a challenge. With regard to the influence of background systems on the input material flows, the number of parameters required is mainly limited to the rMSW material composition, the energy supply and the climatic conditions of the background system. Thereby, the influence of different drivers on the rMSW composition is an issue to be considered carefully. The selection of material groups that are modelled must be able to reflect all potential changes relevant for the results of the model on the one hand. On the other hand, data for these material groups must be available. rMSW characterization methods are to be taken into account when selecting material groups for modelling. Hereby, the characterization of fine particles, which cannot be separated manually into material groups, is particularly challenging. The influence of different drivers on the material inputs other than rMSW are not identified to create major problems for modelling, as they are either simple information (temperature, humidity) or well represented by data bases (energy).

The output materials are strongly influenced by the judicial context and the market situation that an rMSW treatment technology is implemented in. All parameters related to the output flows that were identified as being relevant for the climate performance and driven by the background system show the potential to demand technological add-ons to the foreground technologies of the investigated MBT and incineration technologies. Different judicial thresholds for air and water emissions typically demand different levels of waste air and waste water cleaning, which would have to be modelled within the foreground system. From experience, there are no models that allow to flexibly modelling all processes of the investigated rMSW treatment technologies in such a detailed manner that information about the concentrations of the parameters related to air and water output flows in Table 2 could be obtained by reaction equations on a molecular level. Thus, generic data of the content of specific substances have to be linked to the input material groups modelled and generic transfer coefficients have to be applied for processes. The same is true for thresholds related to landfill material and RDF.

With regard to further research work, one of the next steps towards a comprehensive model that allows modelling GHG emissions from MBT and incineration in different contexts is the specification of relevant add-on technologies and the determination of applicable transfer coefficients for the add-on technologies in question. Thereby, it must be ensured that the transfer coefficients for such technologies, if necessary, again can be adapted to varying background conditions.

What is more, the impact of varying rMSW input compositions and/or climate conditions on biological processes must be further investigated, as there is hardly any quantitative information available about the correlation of these parameters and the kinetics taking place during biological treatment processes.

Policies increasingly focus on secondary raw materials. At the same time, numerous countries within EU and also outside EU need to establish rMSW treatment technologies. Thus, the demand for a robust model of different MBT and incineration technologies including post treatment processes can be expected to remain an issue of concern in the near and medium term future. Thus, it should be further investigated, even though modelling in this field is complex and developing applicable models represents a challenge due to the complexity of the systems and the high number of variables that play a role when modelling the GHG emissions from MBT and incineration. In order to keep a correspondent model handable, future research may investigate, if and which parameters may be neglected for modelling as of their minor relevance for the results. This is especially important with regard to the role of the indirect GHG emissions. On the other hand, modelling may be extended by the inclusion of additional life cycle impact categories and additional technological approaches, such as anaerobic digestion of rMSW. In [26], a model is presented, which allows determining the GHG emissions from the above described scenarios and additional selected technological add-ons for material recovery, landfill gas recovery and energy recovery. The model is based on the above described interdependencies between the climate performance of rMSW treatment technologies and the framework conditions it takes place in. The publication includes mathematical dependencies and exemplary calculations using data from operating plants and research conducted at the Department of Processing and Recycling, RWTH Aachen University with regard to varying rMSW compositions and MBT technologies. Findings from [26] with regard to the quantitative significance of varying background conditions on the GHG emissions balance of different rMSW treatment technologies will be presented in separate publications as to the limited scope of this publication.

Comment: Part of the content of this paper is taken from the first author's dissertation [26]. Related quotations, both direct and indirect, are not specifically highlighted.

References

1. SASE: Wiederaufbau, Wirtschaftswunder, Konsumgesellschaft.Stadtentwicklung, Stadthygiene, Städtereinigung und Abfallwirtschaft in Deutschland 1945 bis 1975. SASE Schriftenreihe Urbaner Umweltschutz Band 2 (2014). ISBN: 978-3-9813894-1-8
2. United Nations: Kyoto Protocol to the United Nations Framework Convention on Climate Change. United Nations Framework Convention on Climate Change. http://unfccc.int/resource/docs/convkp/kpeng.pdf (1998). Accessed 10 June 2014
3. The European Parliament and the Council: Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain directives. Off. J. Eur. Union. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0098&from=EN (2008). Accessed 10 Oct 2014
4. The Council of the European Union: Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste. Off. J. Eur. Communities. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31999L0031&from=EN (1999). Accessed 10 Oct 2014
5. Jackson, C., Watkins, E.: EU Waste Law: The Challenge of Better Compliance. Institute for European Environmental Policy, London (2012)
6. European Commission—Joint Research Centre—Institute for Environment and Sustainability: International Reference Life Cycle Data System (ILCD) Handbook—General guide for Life Cycle Assessment—Detailed Guidance. First edition March 2010. EUR 24708 EN. Publications Office of the European Union, Luxembourg (2010). ISBN: 978-92-79-19092-6, ISSN: 1018-5593. doi:10.2788/38479
7. Montejo, C., et al.: Mechanical-biological treatment: performance and potentials. An LCA of 8 MBT plants including waste characterization. J. Environ. Manag. **128**, 661–673 (2013)
8. Steiner, M.: Stand der mechanisch-biologischen Restabfallbehandlung in Europa. In: 6. ASA Abfalltage. Tagungsband: Mechanisch biologische Restabfallbehandlung MBT in der Bewährung. ORBIT (2006) ISBN-13: 978-3935974080
9. Laurent, et al.: Review of LCA studies of solid waste management systems—part I: lessons learned and perspectives. Waste Manag. **34**, 573–588 (2014)
10. Cleary, J.: Life cycle assessments of municipal solid waste management systems: a comparative analysis of selected peer-reviewed literature. Environ. Int. **35**, 1256–1266 (2009)
11. Laurent, et al.: Review of LCA studies of solid waste management systems—part II: methodological guidance for a better practice. Waste Manag. **34**, 589–606 (2014)
12. IPCC 2006, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T., Tanabe K. (eds). Published: IGES, Japan
13. European Commission: Integrated Pollution Prevention and Control Reference Document on the Best Available Techniques for Waste Incineration. http://eippcb.jrc.ec.europa.eu/reference/BREF/wi_bref_0806.pdf (2006). Accessed 10 Oct 2014
14. Quicker, P., Noël, Y.: Alternativen zur Verbrennung? In: Karl, J., Thomé-Kozmiensky, K. J., Beckmann, M. (eds.) Energie aus Abfall—Band 11, pp. 767–778. TK Verlag Karl Thomé-Kozmiensky, Neuruppin (2014). ISBN: 978-3-944310-06-0
15. Arbeitsgemeinschaft Stoffspezifische Abfallbehandlung (ASA): MBA-Steckbriefe—Fact Sheets on German MBT plants 2010/2011, ASA GmbH (2010)
16. DWA Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e. V.: Merkblatt DWA-M 388 Mechanisch-Biologische (Rest-)Abfallbehandlung (MBA), DWA-Regelwerk (2014). ISBN: 978-3-944328-52-2
17. European Commission: Integrated Pollution Prevention and Control Reference Document on the Best Available Techniques for the Waste Treatment Industries. http://eippcb.jrc.ec.europa.eu/reference/BREF/wt_bref_0806.pdf (2006). Accessed 17 Apr 2015
18. Kranert, M., Cord-Landwehr, K.: Einführung in die Abfallwirtschaft 4. Auflage, Vieweg + Teubner Verlag, Springer Fachmedien Wiesbaden GmbH (2010). ISBN: 978-3-8351-0060-2
19. Cuhls, C. et al.: Emissionen aus der Kompostierung und Vergärung von Bioabfällen im Vergleich. In: Proceedings 2. Biomasse-Forum 2008, pp. 299–320. http://www.ask-eu.de/Artikel/14101/Emissionen-aus-der-Kompostierung-und-Verg%C3%A4rung-von-Bioabf%C3%A4llen-im-Vergleich.htm (2008). Accessed 09 Oct 2014
20. Johnke, B.: Emissions from waste incineration. Background paper. In: Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. IPCC National Greenhouse Gas Inventories Programme, Japan, 2001. http://www.ipcc-

nggip.iges.or.jp/public/gp/bgp/5_3_Waste_Incineration.pdf (2001). Accessed 10 Oct 2014
21. Coskun et al., Advanced exhaust air treatment for MBT plants. In: The 28th International Conference on Solid Waste Technology and Management Philadelphia, PA, USA, March 10–13, 2013, pp. 760–770 (2013). ISSN: 1091-8043
22. Beyer, C.: Modellierung und Simulation von Abfallbehandlungsanlagen unter besonderer Berücksichtigung der Stoffstromvektorisierung, Shaker, Aachen (2002). ISBN: 3-8322-0570-5, ISSN: 1617-6545
23. Bauerschlag, N. et al.: Modernization of composting plants by implementation of a bio leaching system. In: Proceedings of the 7th International Conference ORBIT 2010: Organic Resources in the Carbon Economy, Heraklion, Greece, June 29–July 3, 2010. Europ. Compost Network (2010). ISBN: 978-960-6865-28-2
24. Bundesministerium der Justiz und für Verbraucherschutz: Gesetz für den Ausbau erneuerbarer Energien (Erneuerbare-Energien-Gesetz—EEG 2014). juris GmbH. http://www.gesetze-im-internet.de/bundesrecht/eeg_2014/gesamt.pdf (2014). Accessed 10 Oct 2014
25. Bundesministerium der Justiz und für Verbraucherschutz: Gesetz über die friedliche Verwendung der Kernenergie und den Schutz gegen ihr Gefahren (Atomgesetz—AtG). juris GmbH. http://www.gesetze-im-internet.de/bundesrecht/atg/gesamt.pdf (2013). Accessed 10 Oct 2014
26. Clausen, A: Mechanical biological treatment processes in consequential carbon footprint modelling of residual MSW management. Approved dissertation, submitted to the Faculty of Georesources and Materials Engineering, RWTH Aachen University at 9th of April 2015 (in press)
27. The Treasury: 2009 No. 1929 Landfill Tax (Prescribed Landfill Site Activities) Order 2009. http://faolex.fao.org/docs/pdf/uk89735.pdf (2009). Accessed 10.10.2014
28. Bundesministerium der Justiz und für Verbraucherschutz: Gesetz zur Förderung der Kreislaufwirtschaft und Sicherung der umweltverträglichen Bewirtschafung von Abfällen (Kreislaufwirtschaftsgesetz—KrWG). juris GmbH. http://www.gesetze-im-internet.de/bundesrecht/krwg/gesamt.pdf (2012). Accessed 10 June 2014
29. The European Parliament and the Council: Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control). Off. J. Eur. Union. http://europa.eu/legislation_summaries/environment/soil_protection/ev0027_en.htm (2010). Accessed 10 June 2014
30. Bundesministerium der Justiz und für Verbraucherschutz: Verordnung über die umweltverträgliche Ablagerung von Siedlungsabfällen (Abfallablagerungsverordnung—AbfAblV). juris GmbH. http://www.gesetze-im-internet.de/bundesrecht/abfablv/gesamt.pdf (2009). Accessed 10 June 2014
31. Bundesministerium der Justiz und für Verbraucherschutz: Siebzehnte Verordnung zur Durchführung des Bundes-Immissionsschutzgesetztes (Verordnung über die Verbrennung und die Mitverbrennung von Abfällen—17. BImSchV). juris GmbH. http://www.gesetze-im-internet.de/bundesrecht/bimschv_17_2013/gesamt.pdf (2013). Accessed 10 June 2014
32. Bundesministerium der Justiz und für Verbraucherschutz: Dreißigste Verordnung zur Durchführung des Bundes-Immissionsschutzgesetztes (Verordnung über Anlagen zur biologischen Behandlung von Abfällen—30. BImschV). juris GmbH. http://www.gesetze-im-internet.de/bundesrecht/bimschv_30/gesamt.pdf (2009). Accessed 10 June 2014
33. Bundesministerium der Justiz und für Verbraucherschutz: Verordnung über Anforderungen an das Einleiten von Abwasser in Gewässer (Abwasserverordnung—AbwV), juris GmbH. http://www.gesetze-im-internet.de/bundesrecht/abwv/gesamt.pdf (2004). Accessed 10 June 2014