2018.06.11
Updated
Version
6689229

D3.6 – Report on results for household food waste collection and decentralised shredding in the "Lübeck-case"

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 689229.

DECISIVE

A DECENTRALISED MANAGEMENT SCHEME FOR INNOVATIVE VALORISATION OF URBAN BIOWASTE

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 689229.

A Decentralised Management Scheme for Innovative Valorisation of Urban Bio-waste

Grant Agreement N°	6689229		
Acronym	DECISIVE		
Full Title	A Decentralised Management Scheme for Innovative Valorisation of Urban Bio-Waste		
Work Package (WP)	3.2		
Document Type	Deliverable		
Document Title	Report on results for household food waste collection and decentralised shredding in the « Lübeck case »		
Dissemination Level	**CO**	Confidential, only for partners of the Consortium (including the Commission's Services)	
	PU	Public	**X**
	PP	Restricted to other programme participants (including the Commission Services)	
	RE	Restricted to a group specified by the Consortium (including the Commission Services)	

Document History

Version	Date	Editor	Modification
Draft 01	29.11.2017	TUHH	First draft for principal structure submitted
Draft 02	15.12.2017	TUHH	Upgrade after feedback of contributors received
Draft 03	11.01.2018	TUHH	Feedback of contributors incorporated
Last Draft	16.02.2018	TUHH	Feedback of contributors incorporated
Last comments to last Draft	20.02.2018	TUHH	Feedback of contributors, reviewers and coordinator
Release	26.02.2018	TUHH	First release for approval by coordinator
Submitted	28.02.2018	TUHH	Submitted to the Coordinator
Distribute	28.02.2018	TUHH	Distribution to DECISIVE partners
Update submitted	11.06.2018	TUHH	Submitted to the Coordinator
Update submitted	12.06.2018	IRSTEA	Submitted to the Commission

Authorship

Name	Organisation	Contact
Jessica Schermuly Steffen Walk Victor Oyedele Antonio Arroyo Cuara Ina Körner	**TUHH** Hamburg University of Technology, Germany	jessica.schermuly@tuhh.de steffen.walk@tuhh.de victor.oyedele@tuhh.de antonio.arroyo.cuara@tuhh.de i.koerner@tuhh.de
Stefan Deegener	**INFRANOVA** Lübeck, Germany	deegener@tuhh.de

Contributors

Name	Organisation	Contact
Daina Romeo Marianne Thomson	**AU** Aarhus University, Denmark	daina.romeo@envs.au.dk mth@envs.au.dk
Binnur Kuscu Julian Baur David Wardle Akash Ananth	**TUHH** Hamburg University of Technology, Germany	

Reviewers

Name	Organisation	Contact
Pierre Thiriet	**IRSTEA** Institut national de recherché en sciences et technologies pour l'environnement et l'agriculture, Rennes, France	pierre.thiriet@irstea.fr
Jean-Benoît Bel	**ACR+** Association des cites et des regions pour le recyclage et la gestion durable des ressources Brussels, Belgium	jbb@acrplus.org

Acknowledgement

We would like to thank Lübecker Entsorgunsbetriebe (EBL), but especially Manfred Rehberg and Andreas Willert for providing the location, their support and guidance during the waste composition analysis in the MBT Lübeck. We also thank the staff from EBL for sharing Lübeck waste data. Furthermore, we also thank Prof. Dr. Ralf Otterpohl and Uwe Isberner for sharing valuable experiences and their support during inventories at the eco-settlement LF. Thanks to Jörn Heerenklage for providing equipment for a waste composition analysis.

Document DOI: https://doi.org/10.15480/882.1706

ORCID: 0000-0003-3294-5052 **(Steffen Walk)**
0000-0002-8937-5970 **(Ina Körner)**

Executive Summary

DECISIVE investigates decentralised bio-waste management schemes with micro-scale anaerobic digestion (mAD) as the technological core unit. It also aims at providing a decision support tool (DST) to compare bio-waste management scenarios. This study focuses on the collection of food waste (FW) as the core-substrate of DECISIVE with connection to mAD. These issues are investigated in a case-study performed at the eco-settlement Lübeck-Flintenbreite (LF), which is part of the City of Lübeck (LC). Within the study, the locations are characterised, whereby LF references specifically to settlement structures and LC focuses on the current applied collection and treatment procedures for bio-waste including source-separated bio-waste from biobins and non-separated bio-waste from residual waste bins. A waste composition analysis was carried out for wastes from bio-waste bins and residual waste bins comparing waste qualities. A special focus was placed on FW, which was distinguished into 10 different fractions. Furthermore, an inventory of the technical infrastructure from LF was carried out. In LF a complete mAD system is available. It was constructed in an earlier project, but is yet to be operated. Specifically, the interface between source-separated bio-waste collection and mAD was investigated: the available decentralised shredder was operated with various source-separated bio-waste samples. Finally, scenarios for the transition of LF towards decentralised bio-waste management and the usability of the available mAD process units were evaluated.

The initial concept for LF was to combine blackwater and source-separated bio-waste management at a decentralised level. It was intended to treat the blackwater, orginating from vacuum toilets, together with the household's source-separated bio-waste on-site in a mAD unit. The innovative parts of blackwater collection are in operation, but the bio-waste is still conventionally collected. The mAD with all the pre-treatment parts is not in use.
The current source-separated bio-waste and residual waste collection from LF is integrated in the entire city's collection system and operated by the Waste Authority Lübeck (Entsorgungsbetriebe Lübeck, EBL). The waste composition analysis of source-separated bio-waste and residual waste samples collected by EBL revealed that most of the generated FW is disposed with the residual waste, and that the biobin is used by citizens mainly for garden waste. The waste composition analysis performed in December 2017 included 32 waste fractions for source-separated bio-waste and residual waste, respectively. Considering all results from the waste composition analysis compared to the evaluated German literature, following key data for scenario calculations was defined: 1-5% macro-impurity content of source-separated bio-waste, and 60-90 kg FW per capita and year, which is currently contained in residual waste and in bio-waste. Furthermore, a long-term goal for 50% FW avoidance of the currently collected FW was assumed. Key findings from the analysis of the LC-samples regarding principal avoidability were the following: 40% of FW from source-separated bio-waste was classified as „avoidable" while it was even 81% of the FW from residual waste. The FW content found in residual waste samples was 35% and 7% in source-separated bio-waste samples.

Source-separated bio-waste fractions from the waste collected during the aforementioned waste composition analysis were used to test the decentralised shredding system available at LF. The intention of shredding is to prepare the source-separated bio-waste for wet fermentation and co-fermentation at the mAD unit available in LF. It was found that the shredding system worked well for green garden waste fractions between 10 and 40 mm. However, larger garden waste samples resulted in blockages of the transport system. The same was found for bio-waste including macro-impurities. FW resulted in clogging of cutting blades. Further tests are necessary to find solutions to overcome problems experienced. Different grinding aggregates should also be considered when further testing is conducted. The ground output from the shredding system had a particle size <3 mm, which is ideal for the intended mAD. The volatile solids contents (VS) ranged between 55 and 80% of total solids (TS) with higher values found in the FW, while the garden waste fraction (specifically 10-40 mm) was lower. If garden waste is to be used as a mAD co-substrate, consideration needs to be taken to reduce the inorganic content during the collection phase. The bulk density increased in all grinding tests drastically, e.g. FW increased from 0.37 to 0.8 kg/L. This

is advantageous considering the throughput capacities in mAD. It is also beneficial in the case that mAD would not be applicable; the compaction would improve transport properties.
Based on LF infrastructure inventory, waste composition analyses and shredding experiments, scenarios for further development of the LF regarding source-separated bio-waste collection and decentralised mAD were provided. In total 2 scenarios, each with some sub-scenarios, were developed. All contained a decentralised mAD unit (50 m³) and a pre-treatment to reduced particle size. In all scenarios, FW and blackwater of LF is to be treated together. Scenario 1 includes a door-to-door collection system and the use of the available shredder as grinding device. Scenario 2 includes the installation of a FW disposer in each household to avoid subsequent collection and with the intention of increasing bio-waste quality. Both scenarios showed that it takes approximately a 12-fold amount of FW compared to the available amounts in LF to run the existing mAD plant at full capacity (10% TS). This would therefore imply a major issue if the mAD is intended to be used in future. It does not only depend on the citizens living in LF but also on the waste management company of LC (EBL). The possibilities and concerns of these stakeholders will be evaluated within the progress of the project.

Generally, the results obtained from this study will contribute to a data base contained in the DECISIVE DST. It is meant to support planning, design and assessment of bio-waste management networks in urban areas. The strategies applied for evaluation of the systems in LF and LC will aid in the assessment of future case-studies. The results acquired from this research are fundamental for the development of strategies for transitioning from current bio-waste management systems towards more efficient and innovative ones.

Sources of Fotos

Stefan Deegener
Victor Oyedele
Jessica Schermuly

List of abbreviations

AD	Anaerobic Digestion
CHP	Combined heat and power plant
CAS	Civic amenity site
DD	Door-to-door collection
DST	Decision support tool
EBL	Entsorgungsbetriebe Lübeck (Waste Authority Lübeck)
FM	Fresh matter
FW	Food waste
GDP	Gross domestic product
mAD	Micro-scale anaerobic digestion
LF	Lübeck – Flintenbreite
LC	City of Lübeck
MBT	Mechanical-biological treatment
MSW	Municipal solid waste
NL	Norm litre
PAYT	Pay as you throw
RDF	Refuse derived fuel
SSF	Solid-state fermentation
t	metric tonne (1 t = 1 Mg = 1000 kg)
TS	Total solids
TUHH	Hamburg University of Technology
VS	Volatile solids

Table of content

DECISIVE

List of figures

List of tables

1. Background and study overview

DECISIVE investigates decentralised bio-waste management schemes with micro-scale anaerobic digestion (mAD) as the technological core unit and also aiming at providing a decision support tool (DST) to compare bio-waste management scenarios (DECISIVE 2018: http://www.decisive2020.eu/). *Waste collection* as a major part in each waste management system is also included in DECISIVE. This study focuses on the collection and decentralised shredding of household food waste (FW) specifically for the "Lübeck-Flintenbreite case". Figure 1 displays the interactions of this study with other DECISIVE activities.

Figure 1: Links of the study on "Household food waste collection and decentralised shredding in the Lübeck-Flintenbreite case" to other activity within the DECISIVE project.

The eco-settlement Lübeck-Flintenbreite (LF) was chosen as case study, since at this location various technological units are available, which are important for decentralised FW management. LF is termed as an "eco-settlement" as it was established as an ecologically innovative residential concept for 350 people.

The original planning included an integrated concept consisting of separate collection of wastewater with decentralised on-site treatment of the two fractions greywater and blackwater. The blackwater was to be collected via vacuum toilets and treated by mAD. Furthermore, it was planned to couple the mAD of blackwater with a kitchen waste stream via wet fermentation. For that purpose, a decentralised shredding system was installed to reduce the particle size of the kitchen waste and provide a homogeneous feedstock. LF was planned in 1995, while construction started 1999 (Oldenburg 2015). Despite the complete mAD system being installed it was not in operation until 2018. The separate greywater collection and decentralised treatment is running successful and the blackwater from all inhabitants is collected via vacuum toilets.

The first objective of this study was to analyse the current waste collection and treatment situation of eco-settlement LF (Chapter 2 and 3), which is part of the City of Lübeck (LC). Furthermore, the decentralised kitchen waste shredder, available on-site in LF, is tested and evaluated as a key element for an innovative decentralised FW collection system (Chapter 5). Finally, based on the results, scenarios for the transition from current centralised bio-waste management system towards decentralised ones are presented and evaluated. The main purpose of the scenarios is to display the possibility for successful implementations in the future (Chapter 6). Table 1 gives a short overview of the main contents of the report.

Table 1: Structure of this report with assignments to the evaluated locations (City of Lübeck and/or eco-settlement Lübeck-Flintenbreite as part of the city) and to the timeline

Chapter	Historic/Current Situation										Future Situation						
	System description of the historic/current situation										System description in the future						
	2			3			4				5				6		
Content	Characteristic of the locations			Current procedures for biowaste			Waste Composition analysis				Decentralized biowaste shredding system				Scenarios for decentralized biowaste collection		
Sub-chapter	2.1	2.2	2.3	3.1	3.2	3.3	4.1	4.2	4.3	4.4	5.1	5.2	5.3	5.4	6.1	6.2	6.3
Sub-content	Geography & Deomography	Development	Eco-innovative concept	General & Legislation	Collection	Treatment	Purpose & work programm	Material and Methods	Results	Evaluation	Purpose & work programm	Material and Methods	Results	Discussion	Recent system	New Scenarios	Outlook
Location of evaluation & sampling	Lübeck			Lübeck			Lübeck				Lübeck-Flintenbreite						
	Lübeck-Flintenbreite			Lübeck-Flintenbreite													

Specifically, the following works were carried out within this report:

Chapter 2: Characteristics of the locations: LC and LF

- The geographical and demographical frame conditions of LC as well as of the eco-settlement LF are shortly described (Chapter 2.1).
- An historical overview of Lübeck-Flintenbreite is provided (Chapter 2.2).
- A technical description of the LF innovative concept with the focus on the bio-waste collection and treatment is carried out (Chapter 2.3).

Chapter 3: **Evaluation of current procedures for bio-waste collection and treatment in LC and LF**

- The currently applied collection and treatment procedures in LC and in the eco-settlement LF were investigated (Chapter 3.1, 3.2, 3.3). The eco-settlement LF is recently connected to the general waste collection system of LC. The inventories in LF and LC were executed in close cooperation with INFRANOVA and the “Lübecker Entsorgungsbetriebe” (EBL).

Chapter 4: Waste composition analysis of bio-waste and residual waste of LC

- A waste composition analysis was carried out for residual waste and bio-waste samples; both samples were taken and evaluated in the EBL waste delivery hall. The analysis focuses on various FW groups (including their assignments to avoidable and non-avoidable FW), and other bio-waste and non-bio-waste categories.
- FW is evaluated with focus on quantity and composition from two different collection sources: residual waste and bio-waste bin collections. Results are compared with common data from relevant literature.
- Selected fractions from residual and bio-waste samples of the waste composition analysis were further used for shredding investigations (Chapter 5).

Chapter 5: Application of a decentralised bio-waste shredding system in LF

- Selected bio-waste samples from the residual waste and the separate bio-waste collection (conducted in Chapter 3.) were used to test the shredding system in LF as an innovative way to prepare bio-waste for local valorisation.
- The general performance of the shredder and the process operation parameters (e.g energy consumption, heat development) were evaluated.
- The shredding output (e.g. bulk density, particle sizes) were assessed.
- As a key element of a new decentralised collection system the usability of the shredding output was analysed for co-fermentation with blackwater (small enough particle sizes) respectively for decentralised mAD in general context.
- Selected samples were stored under deep freezing conditions for later micro-impurity analysis.

Chapter 6: Scenarios for decentralised bio-waste collection in Lübeck-Flintenbreite

- Innovative scenarios for the bio-waste collection for decentralised applications are developed as basis for future local decisions in LF.
- The principal options include the available mAD unit and different waste types.
- The scenarios describe in detail the different stages in the collection system (i.e. collection, storage, transport and preparation until its utilisation in a facility).

2. Characteristics of the locations: City of Lübeck and eco-settlement Lübeck-Flintenbreite

2.1 Geographical and demographical overview

Lübeck is a city in Northern Germany situated in the Federal State of *Schleswig-Holstein*. The city of Lübeck (LC) is composed of 10 city-parts and 35 city-districts (Hansestadt Lübeck 2018 a,b) (Figure 2). LC consists of a densely populated "old town" in the centre and less densely populated areas in the surrounding.

The eco-settlement Lübeck-Flintenbreite (LF) is situated close to the outskirts of the city in the district *Sankt Lorenz North* in the dead-end street called *Flintenbreite* (Figure 3).

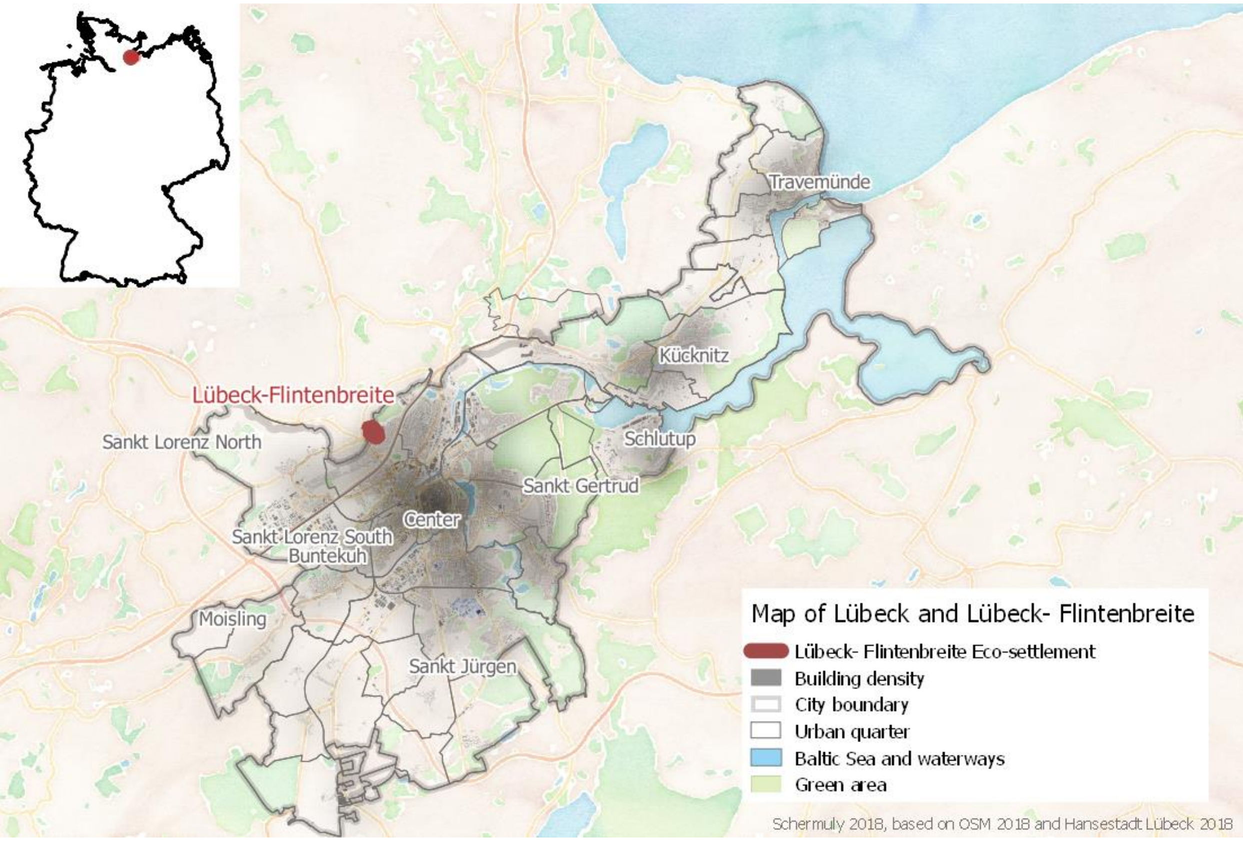


Figure 2: Map of the City of Lübeck with the eco-settlement Lübeck-Flintenbreite

Important geographic and demographic key facts are provided in Table 2 for both, LC and LF. Regarding the climate, both are assigned to the Oceanic climate (Cfb) according to the Köppen-Geiger climate classification system (Geiger 1954).

Table 2: Factsheet of the City of Lübeck and the eco-settlement Lübeck-Flintenbreite

	Unit	City of Lübeck (LC)	Eco-settlement Lübeck-Flintenbreite (LF)
Belonging to:			
Country		Germany	
Region (Federal district)		Schleswig Holstein	
City		Lübeck	
		Whole city	Neighbourhood
Surface area	km²	214.21 [1]	0.054 [2]
Population	Number of inhabitants	216 253[3] 218 523[4]	~250 [2]
Population density	Inhabitants per km²	1010[1]	4 630
Size of private households	Average number of inhabitants per household	1.81 person[5]	3.1
Number of private households		121 969[6]	81
GDP (for Schleswig Holstein)	€ per capita	30 482[7]	

[1] Statistikamt Nord (2015); http://region.statistik-nord.de/detail/10000000000000/1/0/358/
[2] INFRANOVA (2018)
[3] LLUR (2015): Abfallbilanz 2015. Siedlungsabfälle. Landesamt für Landwirtschaft, Umwelt und ländliche Räume des Landes Schleswig-Holstein. Available online at https://www.umweltdaten.landsh.de/nuis/upool/gesamt/abfall/abfall_2015.pdf
[4] Hansestadt Lübeck (2015): Municipal statistical office: Household generation procedure based on the register of registered http://www.luebeck.de/stadt_politik/statistiken/files/PDF/230.pdf
[5] Hansestadt Lübeck (2013-2016): Municipal statistical office: Household generation procedure based on the register of registered http://www.luebeck.de/stadt_politik/statistiken/files/PDF/230.pdf
[6] Hansestadt Lübeck (2016): Municipal statistical office: Household generation procedure based on the register of registered residents: http://www.luebeck.de/stadt_politik/statistiken/files/PDF/230.pdf
[7] Statistische Ämter des Bundes und der Länder (2015): https://de.statista.com/statistik/daten/studie/73061/umfrage/bundeslaender-im-vergleich---bruttoinlandsprodukt/

2.2 Development of the eco-settlement Lübeck-Flintenbreite

LF was planned in 1995 as an ecologic innovative residential concept, designed for 350 inhabitants. The construction of houses including technical installations to handle wastewater and waste started in 1999 (Oldenburg 2015). The technical concept is discussed in chapter 2.3 in more detail. In the first phase the technical infrastructure including mAD and kitchen waste shredder and the community building were constructed. The community building comprises of four flats with the technical equipment located in the basement of the building. The first homes were built in the years 1999 and 2000 and the first 100 inhabitants called “Pioneers” moved into 26 households. They settled in 12 semi-detached households (cyan-blue) and in 14 in row houses (dark-blue) as visualised in Figure 3. This situation remained until the year 2012. At this time a new building company resumed construction of further row-houses. Between 2012 and 2015 approximately 150 further inhabitants called “Newcomers” moved into the 55 new built households (pink and orange, Figure 3). Currently 250 inhabitants live in 81 households. The living space ranges from 110 to 164 m² per household. The settlement was managed until December 2017 by the company “Infranova GmbH”. From January 2018 the owners of the houses founded a new company to manage the settlement self-organised.

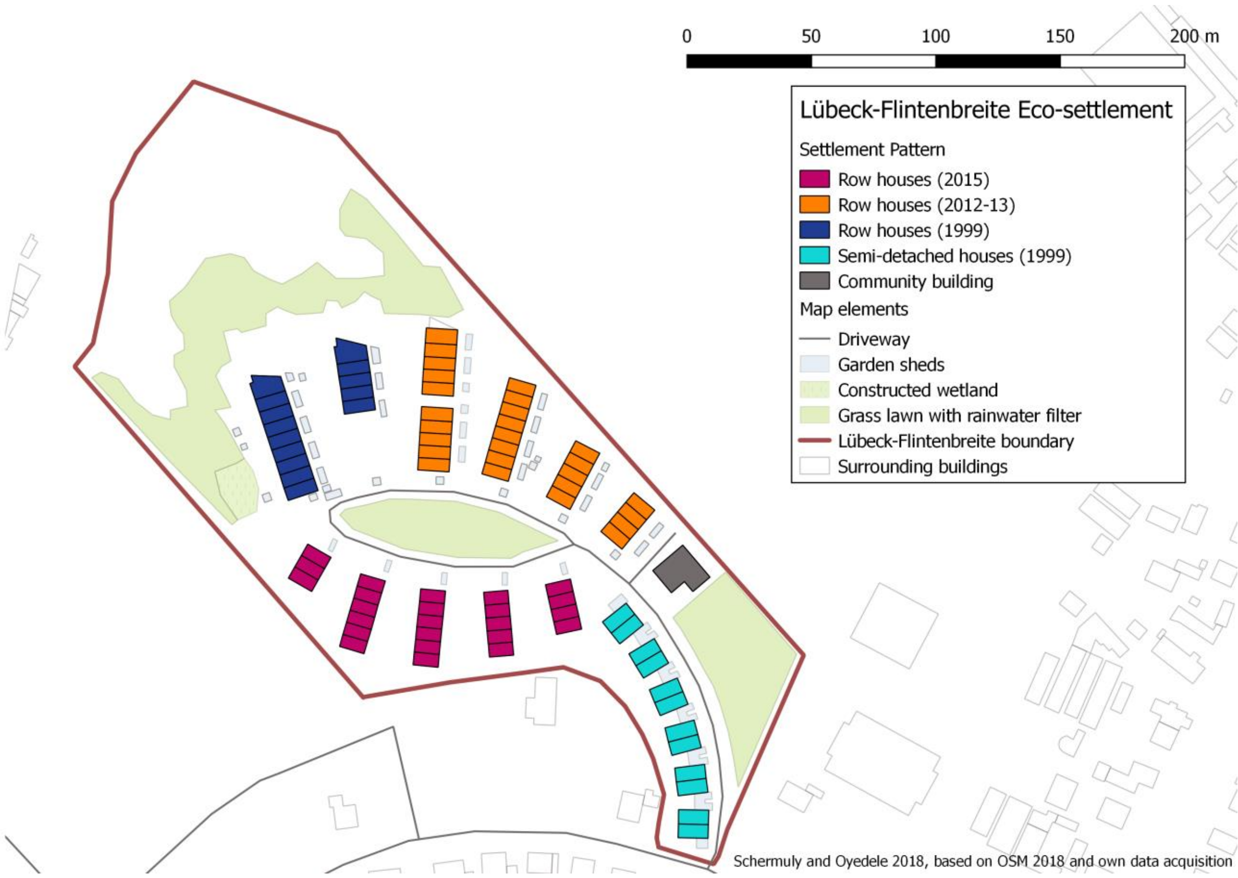


Figure 3: Map of the eco-settlement Lübeck-Flintenbreite including types and settlement years of the building types and location of the community building

The settlement structure and inhabitant profiles of LF vary due to the development of the settlement in stages. The profiles of the inhabitants are characterised stage of settlement as follows:

- **Settlement in year 1999:**
  Pioneers in semi-detached houses (Figure 3; cyan-blue): The Pioneers which moved in the semi-detached houses refer to the first set of inhabitants. Twelve households refer to this group.
  Pioneers in row houses (Figure 3; blue): The first settlers in row-houses, also called pioneers, moved in also in 1999, however, after the *Pioneers in semi-detached houses.* This group included fourteen households.
- **Settlement between 2012 and 2015:**
  Newcomers in row houses (Figure 3; orange and pink): The most recent settlers, "the newcomers" moved in the row-houses which were built in the years 2012/2013 and year 2015. These buildings comprise of fifty-one households.

It is assumed, that the settlement structure may affect the waste collection issues. Proximity and accessibility to waste bins, space within and outside the home, and individual specifics including time availability, trust to waste management systems, as well as ethical aspects (L. Petersen 2017; D 3.5) are known to be of high importance for the behaviours of citizens regarding waste generation, separation and collection. Figure 3 displays the different building types as being marked separately and they also include different inhabitant societies. Ralf Otterpohl, the developer of the Lübeck-Flintenbreite concept and who was for the most part responsible for operation and maintenance of the eco-settlement in the frame of INFRANOVA Company, states:

> *"The profiles of inhabitants differ concerning waste production and waste separation"*
> *"The "Pioneers" are more environmentally conscious than the "Newcomers""*

Therefore, it is expected, that the waste generation, separation and collection performance may vary between the “Pioneers” and the “Newcomers”.

2.3 The eco-innovative concept of Lübeck-Flintenbreite

The initial concept for LF suggested a solution for combined wastewater and bio-waste management at a decentralised level. It was intended to treat the wastewater of all inhabitants as well as their bio-waste on-site. The concept scheme is displayed in Figure 4.

Wastewater:
As the settlement was developed in open countryside it had no connection to the centralised wastewater canalisation system. This was seen as an advantage as wastewater could be separated on site and used as a source of valorisation. Wastewater from households in LF can be broken down into greywater from showers, washing machines and dishwashers and into blackwater from vacuum toilets. Greywater is low in nutrients and organic matter. It is biologically treated and once cleaned infiltrated into the ground water. Blackwater contains nutrients as well as a higher concentration of organic matter since 1) faeces and urine are rich in these substances, and 2) the application of vacuum toilets have the advantage of using less water, reducing dilution and saving drinking water (which is commonly used to flush conventional toilets). The concentrated blackwater was planned to be used in an on-site mAD facility (wet fermentation process) and the digestate to be used in agriculture as fertiliser.

Bio-waste:
Bio-waste from the households was intended to be used on-site in the mAD plant. However, since the mAD is not in use, the waste management company EBL transports the LF waste to the centralised treatment facility of LC (Chapter 3.3). Originally, the bio-waste was intended to be mixed with the blackwater from vacuum toilets, where it would be digested anaerobically in the mAD plant to generate biogas. In order to allow co-fermentation with blackwater, the bio-waste needs to be homogenized and reduced in particle size whereby the mixture would be optimal for wet fermentation. The produced biogas potentially delivers heat and electricity to be used in the settlement via an on-site CHP plant.

Installed devices concerning the mAD unit:
In the basement of the community buildings the following devices were installed in the year 2000:

- vacuum system to enable decentralised blackwater collection
- shredder for preparation of a bio-waste sludge (originally it is an industrial shredder for meat) (Chapter 5)
- mixing tank to mix the bio-waste and the blackwater before feeding the mAD
- hygienisation tank before the digestion reactor to eliminate pathogenic microorganisms
- digestion tank for mesophilic wet fermentation (73m^3 with 23m^3 headspace)
- biofilter packed with wood chips for the exhaust air of the vacuum system

The mAD was designed to be able process the blackwater and bio-waste from 350 inhabitants. At present, only 250 residents live in the settlement (Chapter 2.2), since the construction and selling of houses did not proceed as expected. Due to the lack of residents in LF, the complete mAD system is not in operation yet.
Regardless, the collection and treatment of greywater has been in operation from the beginning. Greywater is treated on-site in two constructed wetlands and one technical treatment plant (fixed bed reactor). The collection of blackwater via the vacuum system is in operation but only collected in a tank to be collected by EBL. It is further processed in the central wastewater treatment plant of LC. The CHP plant is in operation as well but running on fossil gas which supplies the settlement with heat and electricity. Electricity, natural gas and potable water are purchased from external suppliers to supply the settlement. Bio-waste produced from households is conventionally collected as it is done in LC (Chapter 3.2), while garden waste is composted in a decentralised community composting system and the compost is used on-site.

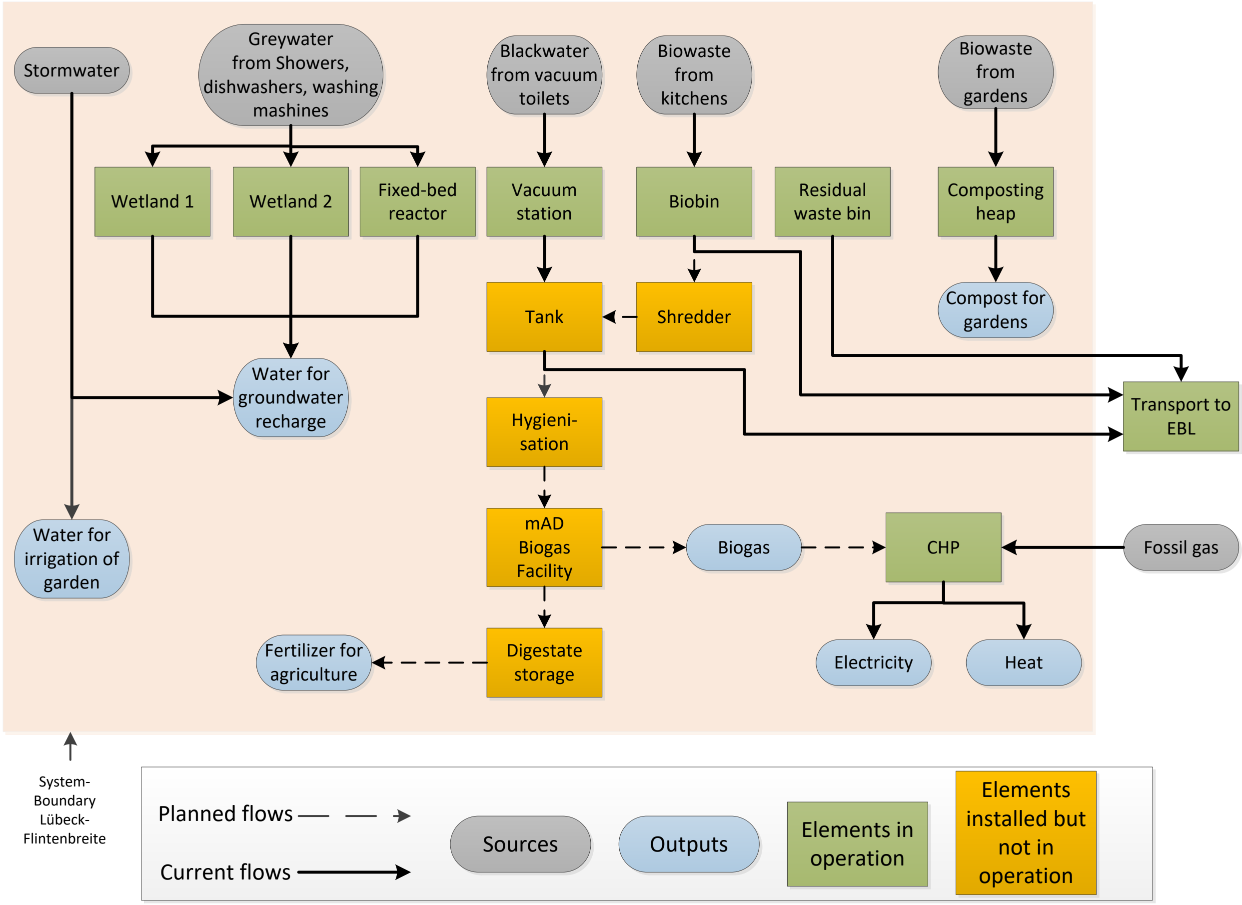


Figure 4: Technical concept and actual situation of the wastewater and waste management in the eco-settlement Lübeck-Flintenbreite

3. Evaluation of current procedures for bio-waste collection and treatment in the city of Lübeck and Lübeck-Flintenbreite

3.1 General situation and legislation

The current waste, collection and treatment practices in Lübeck follow the European, German national and regional legislations. The *Waste Framework Directive 2008/98/EC* sets a standard for the German legislation and is predominately represented by the *German Closed Cycle Management Act* (“Kreislaufwirtschaftsgesetz” KrWG). The KrWG is of specific importance at the national level, since it has made general provisions for the separation of MSW at its source. In detail the KrWG obligates waste producers and waste management authorities to collect bio-waste separately since January 1st 2015.

- The *bio-waste ordinance* (BioAbfV) maintains the requirement in the KrWG to collect bio-waste separately and regulates the source-separation, especially bio-waste. Furthermore, it defines the types of bio-wastes, the treatment procedures in anaerobic digestion and composting, the demanded product qualities as well as correct application procedures.
- *The Regulation on Commercial Wastes* (“Gewerbeabfallverordnung” GewAbfV (2017)) maintains the separate collection, preparation for reuse and recycling of municipal solid waste. It further relays on the classification coding for biodegradable waste fractions according to the “European Waste Catalogue” (EWC 2015).
- *The Regional Waste Management Act (“Landesabfallwirtschaftsgesetz” LAbfWG (1999))* is tailored to the federal state of Schleswig Holstein, giving more region-specific information of the responsibilities of the public administration; the disposal and the collection fees by public waste disposal authorities.
- *The Waste Management Statute (“Abfallwirtschaftssatzung” AbfWS (2014b))* is tailored for LC. It designates MSW disposal companies to collect and recycle separately collected bio-waste, garden waste and FW. According to the mandate EBL is authorised for the collection, handling, recycling and disposal of MSW from households and is responsible for all districts of LC including LF. *AbfWS* states the procedures of compost applications, and clarifies that there are no obligations to self-composting and recycling of biodegradable wastes by private property owners. It further defines, “self-composting” as the full usage of all organic, crop waste, kitchen waste, FW or green waste produced on private property.
- *The Waste Management Fees Statute (“Abfallwirtschaftsgebührensatzung“ AbfWGebS (2014a))* defines the fees of waste collection and disposal in LC.

All waste fractions in LC are accounted for MSW source separation (Table 3). Paper and cardboard, packaging waste including plastic/metal, bio-waste and residual waste are all collected via door-to-door (DD) pickup from houses. Bring points (BP) are established for paper, glass, electronic and hazardous waste. Civic amenity sites (CAS) are available especially for the delivery of garden wastes (green wastes and woody wastes), bulky wastes and eventually contaminated wood waste (Hansestadt Lübeck 2014a,b).

Table 3: Waste collection practices of the most common waste types in the city of Lübeck

Waste collection practice	Responsible waste MSW disposal companies	Waste Type	Fee	Collection type (frequency)
Non source-separated residual waste	EBL Lübeck	Residual waste	Monthly 35 € per 240 L bin	DD (biweekly)
Separate collection of bio-waste	EBL Lübeck	Source-separated Bio-waste	-	DD (biweekly) CAS
Separate collection of recyclables	EBL Lübeck and Entsorgungszentrum Lübeck[2]	Glass	-	BP
	EBL Lübeck	Paper and cardboard	-	DD (monthly / biweekly only in city centre) BP; CAS
	Veolia[1]	Packaging waste	No fee (Disposal tax included in purchasing price of package)	DD (biweekly)

[1] Veolia Umweltservice http://www.veolia-umweltservice.de/gelbe-saecke/
[2] Entsorgungszentrum Lübeck: http://www.entsorgungszentrum-luebeck.de/

The waste collection practices in LF currently do not differ from waste collection procedures in LC.

3.2 Current bio-waste collection procedures

3.2.1 Characteristics of the bio-waste collection system of the city of Lübeck

3.2.1.1 Data of source-separated bio-waste and non-source-separated bio-waste

The collection system for household bio-waste in LC and LF is predominantly carried out via door-to-door (DD) bin pickup. Source-separated bio-waste is collected in biobins, while the remaining unspecified waste is collected via the residual waste bin. Usually non-separated bio-waste is contained in the latter. Both, bio-waste and residual waste bins are frequently emptied biweekly. Table 4 provides data about the collected amounts of source-separated bio-waste and residual waste of LC. It can be estimated that 87 kg per capita and year[1,2] is collected. Official studies do not provide waste data for LF.

Table 4: Data published by the Waste Authority Lübeck (EBL) 2015 and Statistikamt Nord on the collection amounts of source-separated bio-waste and residual waste in Lübeck

Collection Practice	Waste composition	Collected amount (t/year)source	Year
Pickup system (DD)	Residual waste	44 000[1] 44 185[2]	2015
	Bio-waste	16 000[1] 15 570[2]	

[1] EBL Lübeck (2018a): http://www.entsorgung.luebeck.de/ueber_uns/daten_zahlen_fakten/index.html
[2] LLUR (2015): Abfallbilanz 2015. Siedlungsabfälle. Landesamt für Landwirtschaft, Umwelt und ländliche Räume des Landes Schleswig-Holstein. Available online at https://www.umweltdaten.landsh.de/nuis/upool/gesamt/abfall/abfall_2015.pdf

Approximately two years ago (2016), EBL started an inventory of all waste collection bins and containers distributed in LC. Since then, every residual waste, bio-waste and paper bin or container carries a sticker with a QR- code (Figure 5).

Figure 5: QR-code of a waste collection bin of the City (EBL Lübeck 2018d)

Information which is infused in the inventory barcode and saved electronically includes:

- the size and the location of the bin or container,
- the property address to which the bin or container belongs
- a unique ID for each container,
- an internet link via the QR code to an online disposal and pickup schedule with the EBL,
- Information about the bin emptying periods and type of waste collected in a particular container.

The QR code does not include information about waste quantity and quality. The purpose is a basic inventory of waste collection bins and its geolocation in LC. The advantage of the QR code system is that it simplifies the administrative expenses and contributes to an effective pickup- and delivery tour planning and also a better attention to client complaints and requirements (EBL Lübeck 2016).

3.2.1.2 Definition of bio-waste, residual waste and garden waste

Often citizens have problems implementing sorting practices (D 3.5). As assistance for the citizens of Lübeck, EBL provides the sorting instructions via a number of platforms. They are distributed as flyer and information on the EBL website and a service hotline is offered for clients. Table 5 states the waste items which are allowed and not allowed inside residual waste bins and inside biobins according to the regulation of Lübecker Entsorgungsbetriebe (EBL 2017d). The clarification which waste types belong into which bin is crucial for a well working waste collection system.

Table 5: Items allowed and not allowed in the residual waste bin and the biobin in the city of Lübeck

	Residual waste bin	Biobin
		
Items allowed	• Dust bags • Dust from cat litter • Cigarette butts and ash • Ceramic and porcelain wares like plates and pots • Cleaning rags and sponges • Disposable hygiene products like diapers	• Food waste (cooked and raw) • Pre-packaged food waste (without packaging) • Fruits and vegetables (including citrus-fruits) • Coffee set, filter, tea, tea bags • eggshells • flowers, garden trimmings, leaves • tissues, kitchen paper and wrapping paper
Items not allowed	• Toxic substances • Electronic devices, batteries etc. • Soil, sand, stones	• Dust bags; dust from cat litter • Bulky waste (wood) • Soil, sand, stones

[1] EBL Lübeck flyer online available at: http://www.entsorgung.luebeck.de/files/Flyer/infoblatt_abfalltrennung_web.pdf

Garden wastes, such as lawn cuttings and tree trimmings usually occur in large amounts and at varying frequencies during the year (high amount during summer and autumn and low amounts during the winter time from January until March; Adwiraah 2015). EBL provides further options for the inhabitants to handle their garden wastes besides the biobin. The use of biobins for the garden waste is sometimes limited due to space capacities (EBL Lübeck 2017c). Therefore, EBL recommends self-composting some of the bulky garden waste components. Additionally, inhabitants of LC have the possibility to deliver a maximum of 3 m³ of garden waste per year directly to the waste recycling and composting plant (Figure 9) situated in the Waste Management Center Lübeck-Niemark (Chapter 3.3). Furthermore, EBL offers a gratuitous woody garden organics pickup service twice a year. For additional collections, bags for woody garden organics are provided by EBL Lübeck for a fee of 5 € per bag.

3.2.2 Specifics of the bio-waste and residual waste collection in the eco-settlement Lübeck-Flintenbreite

All the statements from chapter 3.1.2 for LC are also valid for LF. Biobins as well as residual waste bins are used in LF (Figure 6).

Figure 6: Biobins (left) and residual waste bins (right) from the eco-settlement Lübeck-Flintenbreite
(Photo: Oyedele 2017)

Specific information about the biobins and residual waste bins:

- ***Biobins:*** In total 20 biobins are distributed at 17 locations within the settlement (Figure 6). The available bins have filling capacities of 80 L (40 kg) and 120 L (50 kg) respectively. The weights are the maximum values given by the bin producers allowing for secure handling as recommended by EBL Lübeck
- ***Residual waste bins:*** Residual waste is disposed in designated bins whereby their filling capacities are either 120 L (50 kg) or 240 L (80 kg)

An important task of the waste collection inventory is the geo-visualisation of the location including houses, bins and other areas. Therefore, a map with the respective information was designed for LF (Figure 7). It enables for instance to calculate transport distances for the houses to the decentralised treatment, to measure the area of the bins and to find new solutions with current systems regarding bin locations.

In order to evaluate the existing systems and compare it with alternative systems location-specific data is necessary. The DECISIVE waste collection database (DECISIVE D3.7) provides a framework to further specific data of local waste storage and transport. In Appendix Table 14 the items of waste storage in and around the housing environment are summarised. The data was gathered specifically for LF biobins and residual waste bins for following items: *bin- volume, bin-costs, bin-water demand for cleaning, device base area, and storage time until transport to treatment.*

DECISIVE

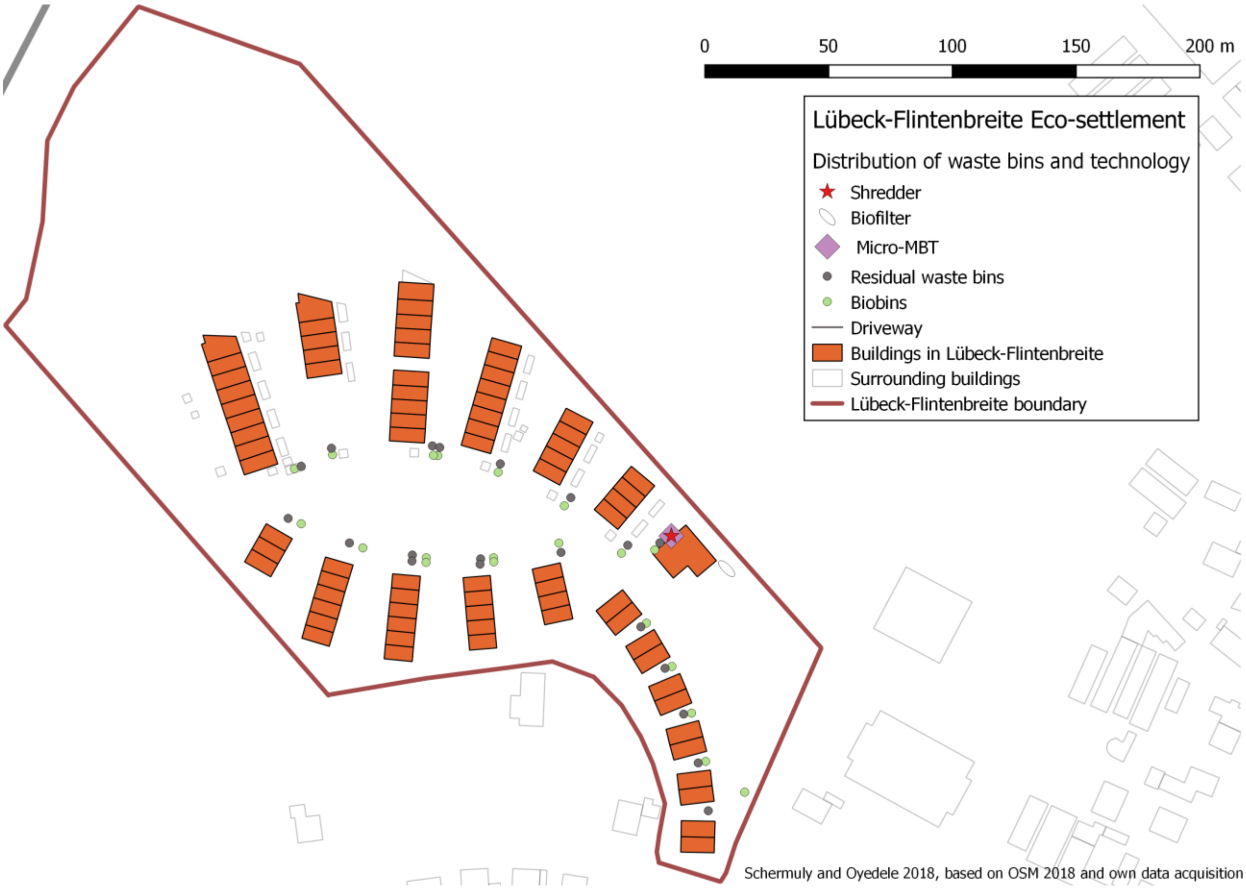


Figure 7: Distribution of biobins in the eco-settlement Lübeck-Flintenbreite

3.3 Currently applied transport and treatment procedures in the city of Lübeck

3.3.1 Transports to the central waste management facility

Currently both, bio-waste and the residual waste from LF are transported and treated in the central waste management facility of LC (Figure 8). This facility is located south-western of the city in the district of Niemark. The shortest distance between the eco-settlement and the waste management facility is 11km. The calculation was done with the path routing feature of Quantum GIS based on open source maps. In the DECISIVE-database (M3, D3.7) certain transport categories are provided. The data was evaluated for current transports of bio-waste (Appendix Table 15) and of residual waste (Appendix Table 16) from LF to the treatment facilities. It describes the following items: *distance, time, fuel demand, manpower demand, average salary, population density, collection point density, transport vehicle volume.*

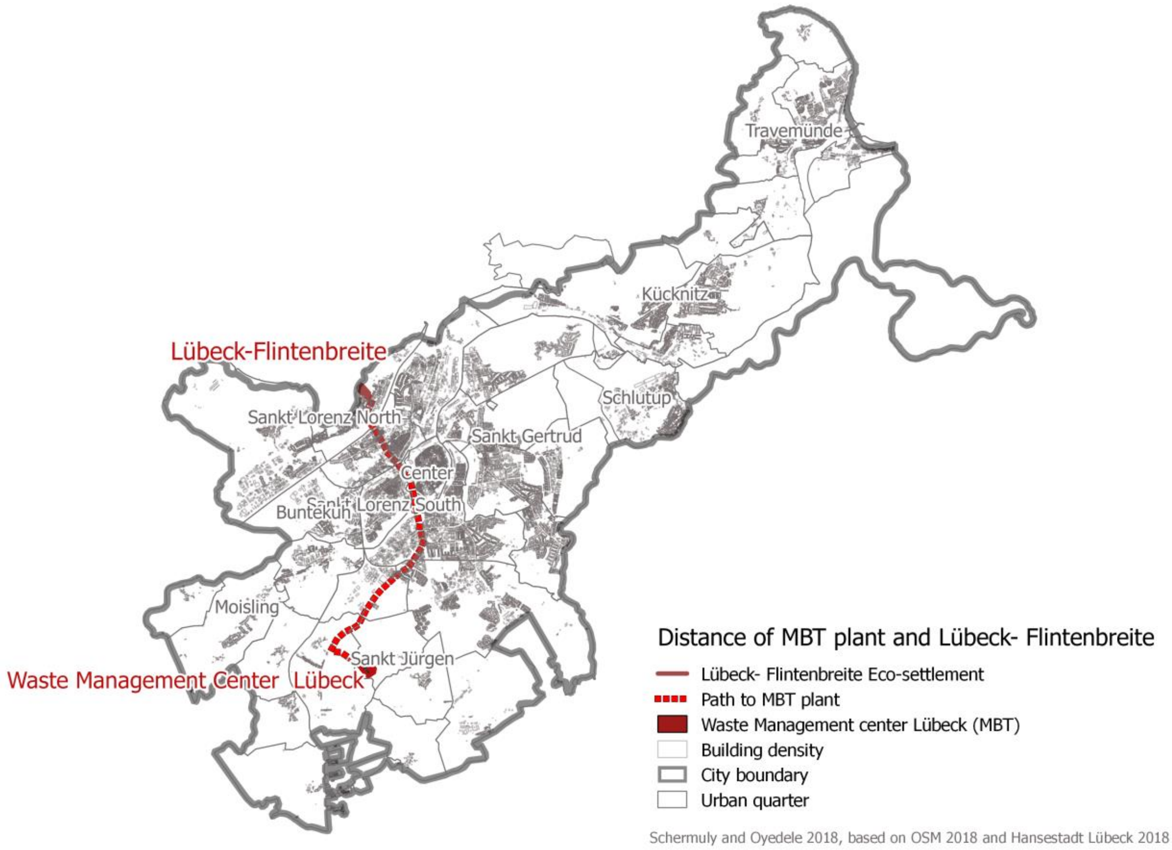


Figure 8: Map of the city of Lübeck with shortest route between the eco-settlement Lübeck-Flintenbreite and the central waste management facility Lübeck-Niemark

3.3.2 Treatment of waste in the central waste management facility

The waste management centre of LC consists of several parts (Figure 9), mainly the mechanical-biological treatment plant (MBT), the composting plant and the landfill. The MBT Lübeck was built in 2005/2006.

Approximately 81,000 t per year of bio-waste and residual waste are delivered to the MBT plant in Lübeck (EBL2016). The waste delivered originates from both, from LC including LF, but also from other smaller cities and villages around Lübeck. It consists of two principal parts – the bio-waste line and the residual-waste line as can be seen in Figure 10. From the delivered 81 000 t, 25 000 t are anaerobically treated in the MBT every year (EBL 2016). The rest is either composted or disposed of in the landfill.

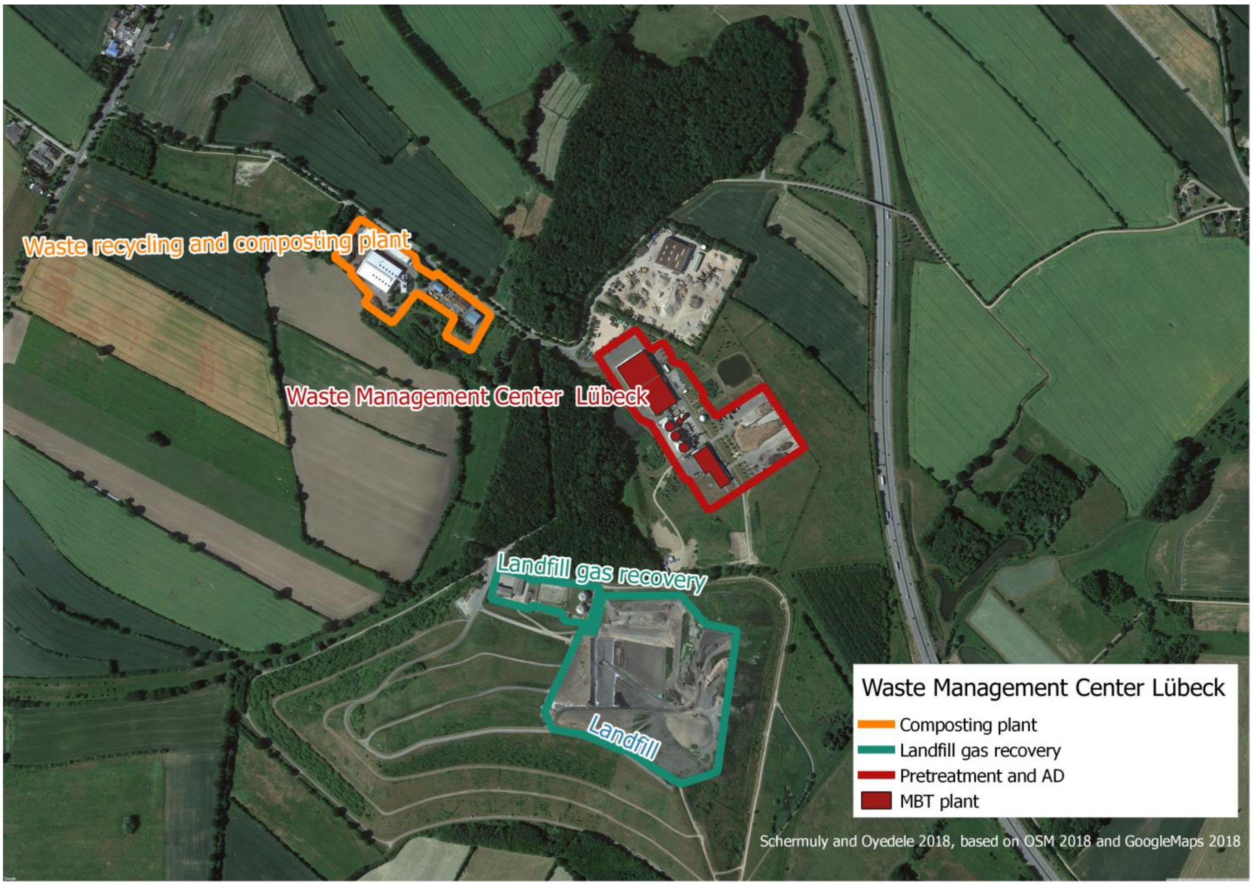


Figure 9: Overview on the waste management centre of the city of Lübeck

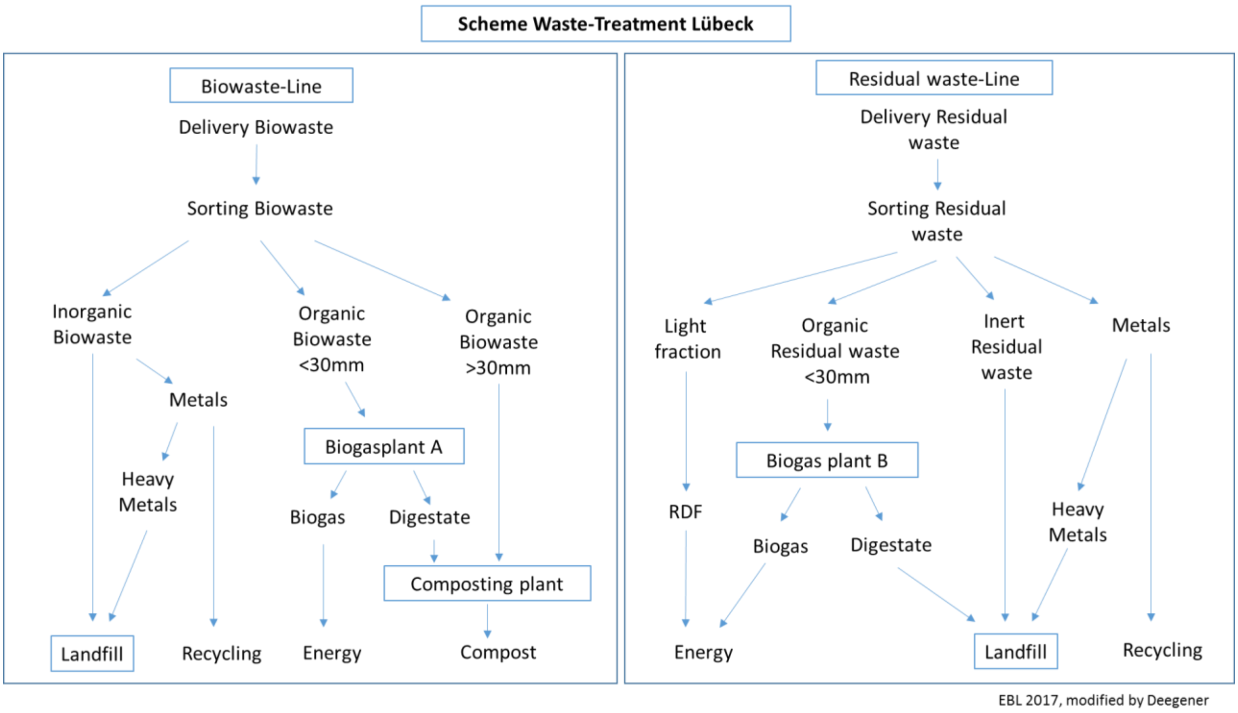


Figure 10: Flow chart of the bio-waste and residual waste material flows in central waste management facility of Lübeck

Figure 10 displays the material flows through the two lines (bio-waste, residual waste) of the MBT and gives information on the outputs of the processes. Both Lines are operated by EBL.

1) Delivered bio-waste and residual waste is registered and then separately placed in the storage hall. In the same hall they undergo mechanical pre-treatment (sorting and shredding).
2) After shredding, metals are removed by a magnetic separation process. Metallic components are separated for recycling, the rest (non-recyclable) is disposed of in the landfill.
3) Next, non-organic fractions are separated from organic fractions:
    - In the *bio-waste line*, the macro-impurities (inorganic, non-metallic waste) are separated from the fine organic bio-waste after the organics are sieved into two fractions (< 30 mm; > 30 mm).
    - In the *residual waste line*, light fractions (mainly plastics and paper) are separated and a product with a high calorific value is generated: Refuse Derived Fuel (RDF). The RDF is used in nearby industries as a supplement to fossil fuel.
4) The fine organic fractions (<30 mm) of the bio-waste and residual waste are used for anaerobic fermentation to produce biogas (EBL Lübeck 2017b). Two bioreactors, one for bio-waste and one for residual waste, are in operation. Both bioreactors produced 2 million m^3 of biogas in 2011 (EBL Lübeck 2016). The biogas is fed into on-site CHP plants, which supply the central waste management facilities and nearby industry with heat and electricity.
5) The digestate from anaerobic fermentation of the bio-waste line is further processed in the composting plant (EBL Lübeck 2017a). In this system, also the larger portion of the bio-waste (>30mm, mainly non-digestible woody waste fractions) are treated. The composting process consists of two phases: intensive rotting in rotting boxes made from concrete as well as curing in open windrows. The compost is used in local agriculture and horticulture (EBL 2017a)
6) The digestate from the anaerobic fermentation of the residual-waste line is used for landfill, as it is deemed too polluted for post-composting. Additionally, the remaining inert waste (about 30% of residual waste) ends up in the landfill (EBL Lübeck 2016).

4. Waste composition analysis of source-separated bio-waste and residual waste of the city of Lübeck

4.1 Purpose and work program

To design a decentralised bio-waste collection chain for the eco-settlement LF it is necessary to have information on the current composition of the collected waste from both, source separated bio-waste from biobins and non-source separated bio-waste from residual waste bins. The waste composition analysis aimed to assess the potential for FW prevention and to increase the capturing rate of bio-waste for valorisation in a source-separated way. Furthermore, it should aid in defining waste fractions which are usable, not-usable or problematic for mAD. This includes the description of the status of current biobin collection regarding macro-impurities.

A waste composition analysis of bio-waste was carried out using waste from the biobin and the residual waste bin of LC whereby samples were taken from the central waste MBT in Niemark. The biobin and residual wastes of LF were collected and centrally treated by EBL (Chapter 3.3) due to the following reasons:

- it is important that a good relationship with the local waste management company EBL Lübeck is established
- the current waste management in the LC is used as a benchmark and as a comparison for all scenarios and future modifications
- the possibility to introduce a decentralised bio-waste management system in the eco-settlement LF is closely connected with general waste management in LC

Several aspects regarding bio-waste composition are important when considering the introduction of a decentralised system in other places. The waste composition analysis performed with the LC waste can be used as a guideline here and in other areas such as Lyon and Barcelona (cases studies for mAD processes within DECISIVE). The main objectives of the waste composition analysis carried out for source-separated bio-waste and residual waste samples from LC can be summarised as follows:

1 **Providing exemplarily waste composition results for waste from bio-bin and residual waste bin** (Chapter 4.2): Acquiring detailed data on the different organic waste fractions inside the collected waste from biobin and residual waste bin is important. Particular focus is set on the avoidable and non-avoidable FW fractions, which are further subdivided into animal- and plant-based FW. From the results the FW prevention potential can be determined with the addition of being able to evaluate further bio-waste fractions usable for mAD, and to determine macro-impurities in mAD.

2 **Comparing waste composition results from LC wastes with results from other German studies** (Chapter 4.3): to decide if the general knowledge is also valid for the situation in the LC and to define values which can be used for calculations of the scenarios for decentralised bio-waste collection schemes.

Furthermore, the sorted organic waste fraction taken from samples from the waste from residual bin and the waste from the biobin were used as material to carry out the further testing of the shredding system from the eco-settlement LF (Chapter 5).

4.2 Materials and methods

4.2.1 Selection of the location of waste sampling

The current waste collection tours of EBL Lübeck do not enable separate waste sampling from LF only, mainly due to anonymity concerns. Therefore, waste samples were taken from the MBT facility in Lübeck-Niemark in cooperation with EBL in December 2017.

For an advanced study it is planned to carry out more detailed waste composition analyses of LF in 2018. Given the privacy issues presented before, an anonymous sampling has to be ensured. The bins are directly allocated to single households and the eco-settlement is divided into different social structures with small sizes (Chapter 2.1). The sampling from LF shall enable that the privacy issues are not concerned and a differentiation of the results to certain structures is possible. A strategy has to be developed to enable both, e.g. by forming of aggregations which are large enough from size to ensure anonymity and/or to obtain the permission of the inhabitants. Furthermore, the comparison of waste samples of specific social structures from the eco-settlement LF with samples from the LC may help to understand any potential differences in waste composition between the two locations.

The results of the conducted analysis do not take into consideration seasonal variation and are therefore not representative for waste composition throughout the year. Therefore, the investigated waste sample described in this study should only be considered as an “example from LC”.

4.2.2 Sampling in the central waste management facility of City of Lübeck

The waste sampling undertaken at the MBT plant in Niemark was carried out by a team from TUHH & INFRANOVA and supported by EBL. Sampling was performed in an indoor hall at EBL. The sampling procedure followed the Saxon Sorting Directive 2014 (LfULG 2014).

Sampling:
Waste samples (source separated bio-waste and residual waste) were obtained upon delivery from the waste collection vehicles of EBL from LC. Source-separated bio-waste and residual waste samples were randomly and separately collected from waste piles and transported into the sorting hall using a pay loader operated by EBL staff. Hereby the individual waste samples were unloaded from the truck in the waste storage area of EBL and a sub sample was taken from each waste. Each sub sample taken from each waste type was weighed and the respective bulk densities determined.

Figure 11: Impressions from the waste sampling and component sorting in the waste management facility plant (Photo: Schermuly 2017)

Left: Weighing of waste samples, using a crane scale; middle: Manual waste sorting of bio-waste *on the topmost sieve (>40mm); right: Manual sorting of residual waste with the 40 mm sieve on top and the 10 mm sieve beneath.*

Volumes and masses determinations

Table 6 shows the measured volumes and masses of the samples taken at the MBT plant in Lübeck. They were determined before the waste component analysis was carried out.

Table 6: Volumes, masses and bulk density of source separated bio-waste and residual waste samples taken at central waste management facility of Lübeck

	Volume [L]	Mass [kg]	Bulk Density [kg/L]
Bio-waste	515	212	0.43
Residual waste	680	158	0.23

Sorting:

After sampling the waste, a sieving procedure was applied (Figure 9) to differentiate the source-separated bio-waste and the residual waste into three size categories:

- > 40mm
- 10 – 40 mm
- <10 mm

The first sieve (mesh size 40 mm) collected large waste components on the top. The second category between 10 and 40 mm was collected by the sieve beneath (mesh size 10 mm) and the components smaller than 10 mm were collected in a receiving container at the bottom. The same sieving procedure was applied separately for source separated bio-waste and residual waste samples. Figure 12 shows the bio-waste components 10-40 mm and <10 mm after sieving.

Figure 12: Bio-waste components 10-40 mm on the sieve and <10mm in the receiving container (Photo: Schermuly, 2017)

Waste items on the sieves were carefully identified and placed in pre-labelled containers assigned with specific waste component fractions. Table 7 provides the list of component categories and fractions where items were assigned to. The differentiation was carried out based on waste sorting from Adwiraah (2015), but further specified in order to fulfil the requirements of DECISIVE.

Table 7: Waste component categories and fractions applied in the waste component analysis for residual waste and the bio-waste

a) Applied for waste size categories > 40 mm

Category no.	Category type		Fraction no.	Fraction type
1	Food waste	Unavoidable FW	1	Preparation remains (animal based)
			2	Preparation remains (plant based)
		Avoidable processed FW	3	Leftovers (animal based)
			4	Leftovers (plant based)
			5	Original packaged food (animal based)
			6	Original packaged food (plant based)
			7	Opened packaged food (animal based)
			8	Opened packaged food (plant based)
		Avoidable unprocessed FW	9	Unpacked original food (animal based)
			10	Unpacked original food (plant based)
2	**Green and woody waste**		11	Garden organics (green waste)
			12	Garden organics (woody waste)
	Wood waste		13	Wood waste (dry)
3	**Glass**		14	Glass
4	**Paper**		15	Paper/cardboard
			16	Tissue
			17	Other paper
			18	Paperbags
5	**Plastic**		19	Plastic
			20	Plasticbags
			21	Biodegradable plastic
6	**Metals**		22	Metal
7	**Electronic & hazardous waste**		23	Batteries, household chemicals, fluorescent light bulbs, paint and small electronic equipment
8	**Non-identifiable waste**		24	Non-identifiable waste

b) Applied for waste size categories 10-40 mm

Category no.	Category type	Fraction no.	Fraction type
9	**Foodwaste**	25	Foodwaste (non specified)
10	**Green - and woody waste**	26	Garden organics (woody waste)
		27	Garden organics (green waste)
	Wood waste	28	Wood waste (dry)
11	**Paper**	29	Paper/cardboard
12	**Non-identifiable waste**	30	Non-identifiable waste

c) Applied for waste size categories < 10 mm

Category no.	Category type	Fraction no.	Fraction type
13	Non-specific waste	31	Liquid
14		32	Solid

Table 7a gives an overview of the different waste categories and fractions considered for the items larger than 40 mm. The inventory table was used to classify both, the source separated bio-waste and the residual waste. The focus of the waste composition analysis was set to FW fractions, since FW is DECISIVEs core substrate. The assignments to the several categories and fractions are based on knowledge from literature and practical experiences during previous waste composition analyses. The following main FW categories were defined:

- **unavoidable FW** comprises of raw food preparation remains, such as potato peels
- **avoidable processed FW** includes leftovers from meals cooked in households as well as opened or untouched industrial processed packaged food, which is usually wrapped in plastic or paper packaging
- **avoidable unprocessed FW** includes original pure food, which is not wrapped in a paper- or plastic package

Each category was further subdivided into animal-based and plant-based FW. The animal-based FW consists of items of only animal origin such as meat, milk, eggs, fish, and seafood including mainly animal-based origin (e.g. sausages and milk products, which may contain plant-based additives such as spices and fruits). Plant-based fractions contain food products exclusively from plant-based origin such as grain and cereal products, fruits and vegetables. Plant-based FW of mainly plant-based origin is also considered (e.g. croissants and cake), despite them containing animal-based additives such as eggs and butter. Animal- and plant-based food have a very different ecological footprint (Körner 2015), therefore a differentiation of these fractions was important.
Waste samples were further separated into 10-40 mm fractions (Table 7b) and <10 mm fraction (Table 7c). In the 10-40 mm fraction, FW was only considered as one category type, since a further subdivision was not possible due to impracticality of sorting. In the same way fractions smaller than 10 mm were dedicated to the fraction "non-identifiable waste". However, they were further subdivided only into solid and liquid fractions, while the organic content was determined in the laboratory afterwards.

Besides FW, additional fractions were determined as shown in Table 7. The > 40 mm and the 10-40 mm fractions of green and woody wastes are different in their properties regarding degradability under anaerobic conditions, therefore they were further subdivided. Green wastes, e.g. from lawn cuttings, leaves, old flowers, are soft and in principle able to be anaerobically degraded. Woody wastes such as twigs and branches are more rigid and in general not anaerobically degradable without pre-treatment, thus it was considered separately. In contrast, wood waste (dry) does not originate from the garden consisting commonly of dry wood products such as old furniture or deconstruction wood which may be contaminated additionally with paints, glues or wood protection chemicals. The paper fractions are also anaerobically degradable, but are better separated for paper recycling. Glass, plastics, metals, electronic and hazardous waste are considered as macro-impurities in bio-waste. All items which were unable to identify were assigned to the mixed cluster of "non-identifiable wastes" in all size categories. Figure 13 displays the waste handling location and the vessels with the waste fractions (listed in Table 7) which were weighted, volumes determined and the bulk density calculated.

Figure 13: Waste component analysis in the waste management facility Lübeck: Arranged and labelled vessels for the different waste types
(Photo Schermuly 2017)

4.3 Results

4.3.1 Recovery rate of source-separated bio-waste and residual waste

Table 8 provides a summary of the waste sorting with a high degree of accuracy shown by such little waste lost while sorting.

Table 8: Mass before and after sorting bio-waste and residual waste

	Mass before sorting (kg)	Masses after sorting (kg)			Sorting losses [% of unsorted sample]
		Fractions > 40mm	Fractions 10-40 mm	Fractions <10 mm	
Bio-waste	219.9	90.9	93.3	28.1	3.5
Residual waste	157.6	122.9	22.2	9.0	2.2

4.3.2 Fractions in the source-separated bio-waste

All following evaluations of the specific waste fractions are based on data presented in the Appendix Table 17 and Table 18. Data includes the fresh weight (in kg and wet w/w%)) from the respective fractions. Figure 14 (based on Table 17 in the Appendix) shows the composition of the bio-waste sample, whereby the largest share (74.8%) with almost three quarters of the overall sample mass comprised of the category green and woody waste. The green waste category was found to be pre-dominantly leaves which can be attributed to the end of the autumn season and increased leaf litter. The second largest share of the bio-waste was that of the "non-identifiable waste" category (13.2%), which consists of fine elements. The FW category shares 7.2 % of the source- separated bio-waste. Plastics, paper and waste wood (dry) could be detected in measurable shares, however pieces of metals, glass, electronic and hazardous waste were found only in very low amounts. 1.5% macro-impurities were found in the total sample mass of source-separated bio-waste.

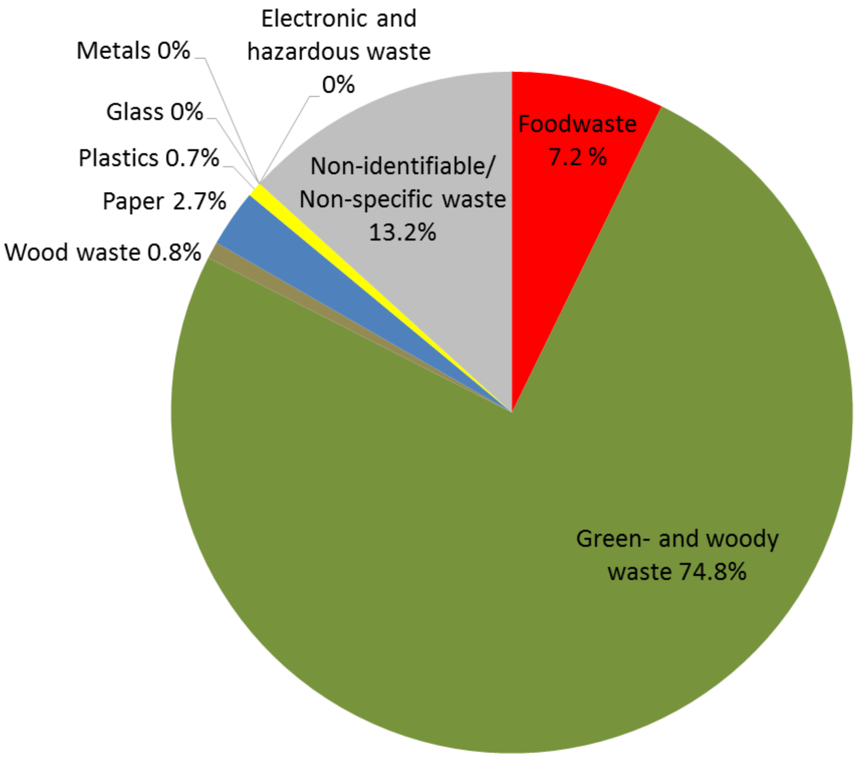


Figure 14: Composition of the bio-waste sample (wet w/w%)

Figure 15 shows the distribution of the FW categories in regards to the avoidability status (based on the definitions from chapter 4.2). As a result, 59 % of the FW category consists of unavoidable FW (highlighted in orange), which are mainly plant-based preparation remains such as potato and banana peels, and orange zest. The avoidable processed FW (highlighted in violet) constituted 30% of the total FW and consisted mainly of food leftovers (animal- and plant based). 10% of the total FW is represented by the avoidable unprocessed FW category (highlighted in blue), which consists mostly of unpacked original food, such as bread and apples.
To conclude 89% of the sampled FW is of plant-based origin with the remaining 11 % from animal based origin Figure 15.

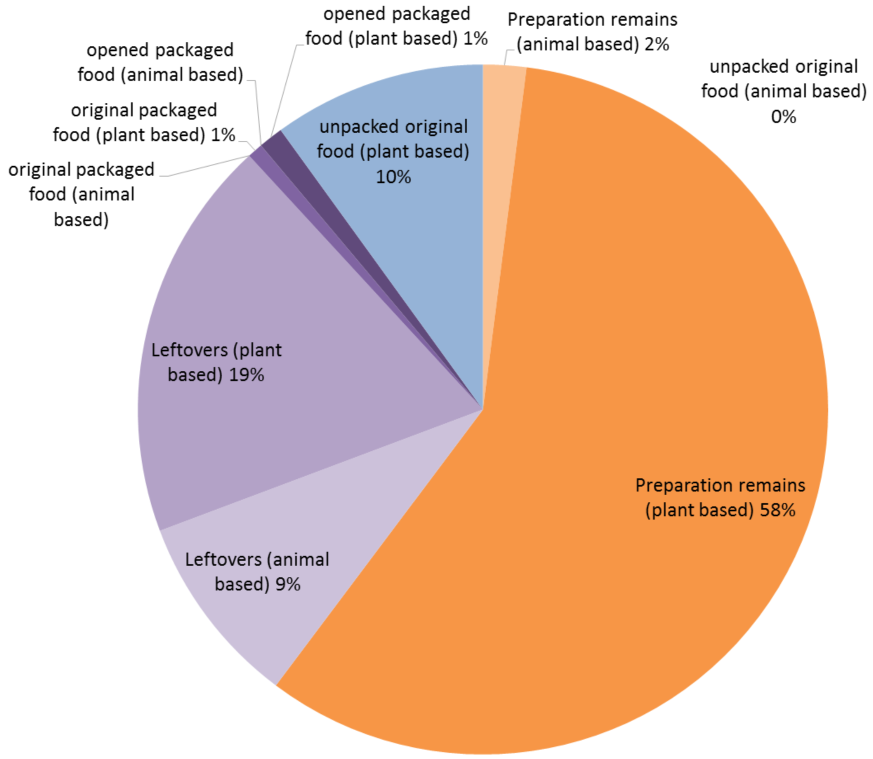


Figure 15: Food waste fractions of the bio-waste sample and their assignment to avoidable and unavoidable food waste categories (wet w/w%)

A summary of avoidable and non-avoidable FW categories is presented in Figure 16, which visualises the FW fraction in the bio-waste sample. Approximately 40 % of the FW in the source separated bio-waste can be considered as avoidable.

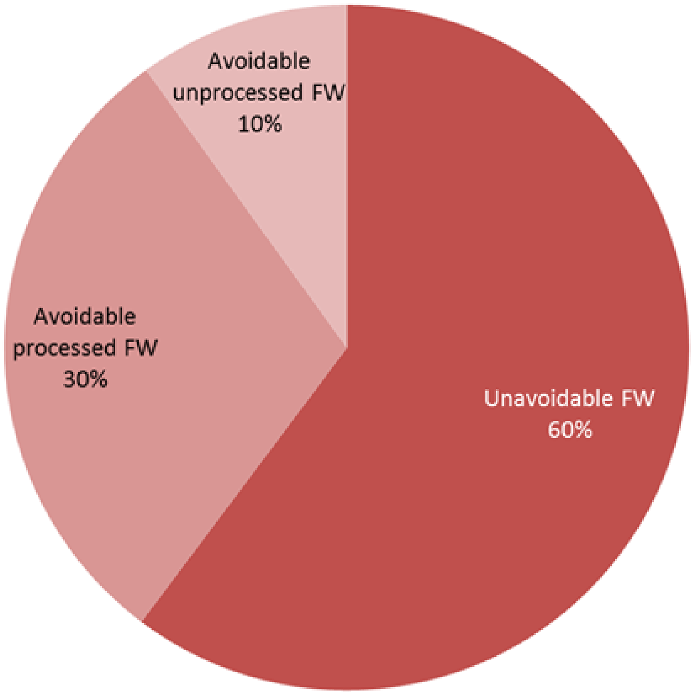


Figure 16: Assignments of food waste fractions in the bio-waste sample regarding their avoidability (wet w/w%)

4.3.3 Fractions in the residual waste

Figure 17 (based on Table 18 in Appendix) shows the composition of the residual waste sample. The share of the FW was much higher when compared to the source-separated bio-waste sample (Figure Figure 14) and was found to be the main fraction in the residual waste. This was followed by paper (24%) and by non-identifiable wastes (17%). Plastics, metals, waste wood and glass followed respectively in small shares. While green and woody waste made up the smallest share with less than 1%. Electronic and hazardous waste was not found.

Based on the current waste management system, the residual waste bin shall pre-dominantly contain non-recyclable fractions. Citizens are expected to use different pathways for recyclables (paper, plastics, metals, and glass) and for FW. However, the total content of recyclables in the residual waste and FW was 43 % and 35 % respectively. This totaled 78 % of residual waste, showing that many fractions are being incorrectly sorted by citizens and could be improved.

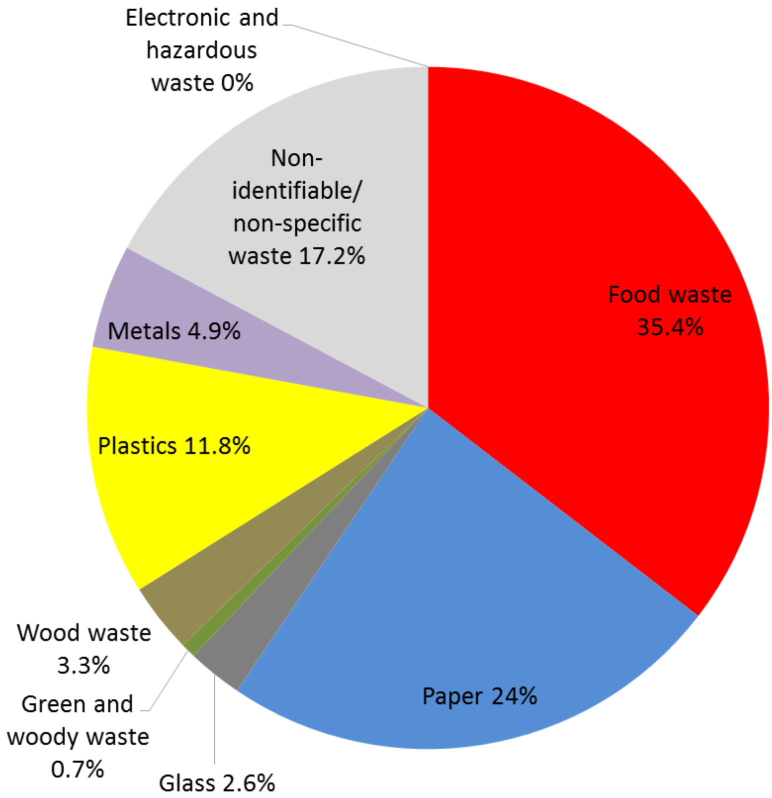


Figure 17: Composition of the residual waste sample (wet w/w%)

Figure 18 presents the composition of FW within the residual waste sample. The largest fraction was the food leftovers (46 %), which was mainly plant-based. The amount of animal-based food leftovers (2 %) was comparatively small, consisting of bones, cooked meat dishes, packed butter. The second largest share of the FW fraction consisted of "opened packaged food" (22%) such as biscuits in a package, packaged bread and potatoes (22%). Food preparation remains, especially plant-based were found as the third largest category (19%).

73% of the FW category consisted of "avoidable processed FW", which comprised of food leftovers, original packaged food and opened packaged food of animal and plant based origin. The amount of "avoidable unprocessed FW" was less than 7%. In the residual waste bin plant-based FWs are predominant with 95% in the FW category of residual waste.

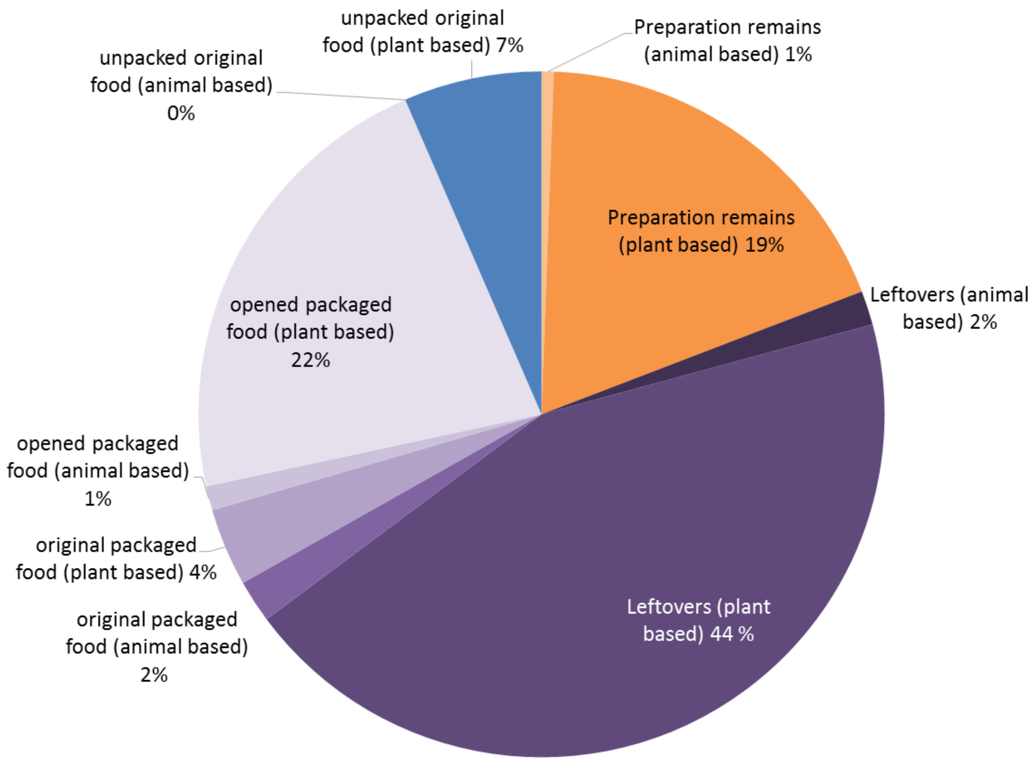


Figure 18: Food waste fractions in the residual waste sample and their assignments to avoidable and unavoidable food waste categories (wet w/w%)

Figure 19 summarises the proportions of the FW fractions in the residual waste sample assigned to their avoidability. Only 19% of the FW fraction in the residual waste sample was considered as unavoidable, while the remaining 81% could be avoided.

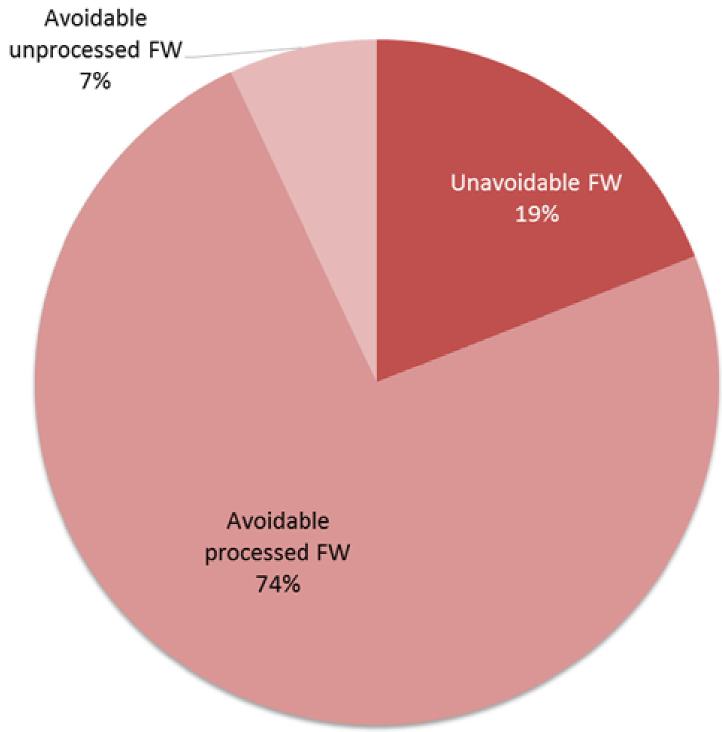


Figure 19: Assignments of food waste fractions in the residual waste sample regarding their avoidability (wet w/w%)

4.4 Evaluation of results

4.4.1 Comparison with other studies from Northern Germany

The results obtained from the waste composition analysis of this study were compared with other studies carried out in Northern Germany:

- Adwiraah (2015) documented results from a waste composition analysis carried out in the district of Bergedorf in Hamburg in 2010 within a scientific project of the TUHH (BERBION). Source-separated bio-waste samples were collected based on housing types (single-family/semi-detached houses, detached houses and multi-family houses) and in different months within a year (September, December, March and June). In this study waste was sorted into 20 different fractions of three different particle sizes (>40 mm; 10-40 mm and <10 mm). The same differentiation of fractions was used as the basis for the waste composition analysis carried out in this study. However, here fractions were subdivided further regarding the DECISIVE demands.
- INFA (Institut for Abfall, Abwasser- und Infrastruktur Management GmbH, Ahlen) conducted a bio-waste composition analysis for the City of Lübeck in 2013. INFA is specialised on waste composition analysis and is known to carry them out for many waste management companies. The analysis conducted at EBL consisted of 12 fractions from residual waste and 6 fractions from bio-waste. The results were not publically published, but provided by EBL to the authors of this study.

No detailed statistical information on source-separated bio-waste and residual waste composition is available however, the statistical office of Northern Germany (Statistikamt Nord 2018) and EBL Lübeck annually publishes information from collected bio-waste and residual waste amounts. Using the available data, it was not possible to perform a more accurate analysis in kg per capita, e.g. INFA provided data only in weight-percentage (w/w%). In order to have comparable results in this report, comparisons were conducted in w/w% as well.

4.4.1.1 Comparison of source-separated bio-waste studies

Macro-impurities in the source-separated bio-waste are of major concern if it is to be valorised in decentralised mADs. In DECISIVE macro-impurities in source-separated bio-wastes were defined as pieces of plastics, glasses and metals (Appendix Table 19). Furthermore, FW is important in regards to DECISIVE as it is the core substrate for mAD, while green garden waste is also considered, as they may be useful as co-substrate. In Table 9 the different fractions of bio-waste of three different studies are summarised.

Table 9: List of bio-waste fractions components analysed in three different studies from Northern Germany and their assignment to the DECISIVE terminology (wet w/w%)

Source	Adwiraah 2015[A]	INFA 2013[B]	TUHH 2017[C]
Year	2010	2013	2017
Location of sampling	HH-Bergedorf	Lübeck	Lübeck
FW / Kitchen- and household waste	5.6	43.9[1]	7.2
Garden waste (green + woody)	78.3	37.8	74.8
Paper	0.9	NA	2.7
Macro-impurities	0.3[2]	2.9[3]	0.7[2]
Other waste	20.6	NA	13.8

[A] Hamburg (Adwiraah 2015)
[B] Lübeck (INFA GmbH 2013)
[C] Lübeck (TUHH 2017)
[1] listed as category kitchen- and household waste
[2] only the Plastic is present in the category "Macro-impurities"; Glass, metals, and electronic and hazardous waste is not represented in the analysed samples
[3] Macro-impurity composition is unknown

Figure 20 summarises the main composition regarding FW, garden waste, paper, macro impurities and other waste of the source-separated bio-wastes described in three studies. Adwiraah (2015) and TUHH (2017) considered only plastics as macro-impurities, while glass, metals and hazardous waste were not found. In the INFA 2013 study, it was not specified which fractions were contained in the macro impurities. Only the general term "impurities" was used and deemed as macro-impurities (Figure 20). All other fractions, which could not be assigned in this way, were placed in the category "Other waste".

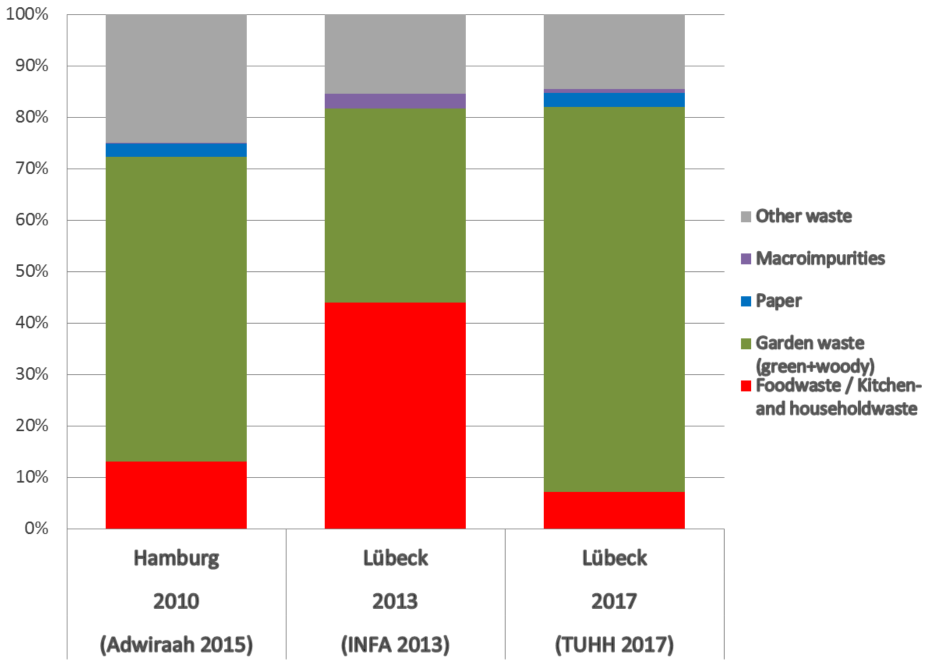


Figure 20: Comparison of the composition of the bio-waste from three different studies carried out in Northern Germany

Data received from EBL did not define the difference between kitchen- and household waste, which can is shown in Figure 20 when comparing to the other studies. However, it can be seen that the category FW is similar between the studies from Adwiraah 2015 and TUHH 2017, which only consider FW and its sub-fractions such as preparation remains, leftovers, fallen fruits and original/opened packaged food as well as unpacked original food. Furthermore, garden waste found in bio-waste samples show some similarity across all three studies; with the TUHH 2017 study having the largest amount, which is most probably due to the time of sampling. Macro-impurities appear to be low across all studies, which is advantageous for valorisation in anaerobic digestion and composting facilities. Based on these results, it could be assumed that bio-waste does not demand specific pre-treatments for cleaning as macro-impurities are low enough to not be a hindrance to the mADs. Therefore, sorting will only be needed to be performed after mAD to fulfil the requirements of BioAbfV regarding impurities in composts or digestates.

4.4.1.2 Comparison of residual waste studies

It is important to know if waste is being sorted effectively whereby for example if recyclables and food waste were found in the correct source-separated bin. For DECISIVE knowledge such as this is essential to be effective in decentralised systems. Modifications to the present residual waste sorting approach can be made to improve the efficiency of the overall system, especially when FW shares are high. Table 10 displays an overview of the fractions for waste types in the residual waste of three different studies.

Table 10: Description of recyclables inside residual waste in three different studies of northern Germany:

Source		Adwiraah 2015[A]	INFA 2013[B]	TUHH 2017[C]
Year		2010	2013	2017
Location of sampling		Hamburg-Bergedorf	Lübeck	Lübeck
FW / Kitchen- and household waste		22.3	27.5	35.4
Garden waste	green- and woody garden waste	14.6	10.0	0.7
Other Recyclables	Glass[A,B,C], Paper[A,B,C], Plastic[A,C], Metal[C], Textiles[B], Light packaging material[B], Electronic and hazardouswaste[B], Batteries[B]	30.1	20.2	43.3
Other waste		33.0	42.3	20.6

A Hamburg (Adwiraah 2015)

B Lübeck (INFA GmbH 2013)

C Lübeck (TUHH 2017)

Figure 21 shows the four classes “FW”, “Garden waste”, “Other recyclables” and “Other waste” which are found in the residual waste. The “Other recyclables” class comprises of plastic[A,C], paper[A,B,C], glass[A,B,C], metals[C], batteries[B], textiles[B], light packaging materials[B] and electronic and hazardous waste[B] (Table 10).

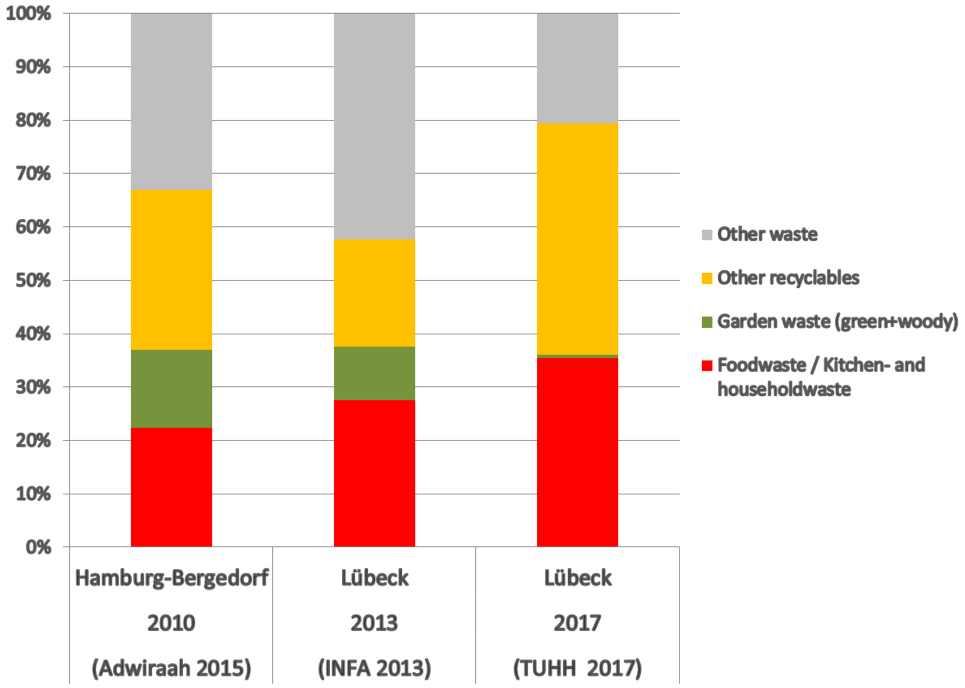


Figure 21: Comparison of the composition of residual waste in three case studies

As seen in Figure 20, a big difference in the garden waste category can be observed between the current study (TUHH 2017) and the INFA (2013) study. It must be noted, however, that the Adwiraah and INFA studies calculated a yearly average based on multiple samples taken throughout the year, while TUHH only considers one sample taken in December. While the same difference in sampling is true for the other recyclables class, not all sources define the same waste categories as described in Table 10. INFA evaluated Glass, Paper, Textiles, Light packaging material, Electronic and hazardous waste and Batteries, whereas Adwiraah (2015) evaluated Glass, Paper, Plastic and TUHH Glass, Paper, Plastic and Metals, respectively. A manifold of reasons hinder a simple comparison of waste composition analyses such as varying methodical assessments, different assignments of waste fractions, variances in the extent of investigation and different temporal and spatial sampling.

In conclusion, there is an important potential of bio-waste that is unsorted, therefore residual waste plays an important role in the innovative concepts idealised. With focus on the transition to new decentralised collection concepts, a better sorting of bio-waste would be required. It is therefore important that the people are willing to contribute to efficient source separation. Furthermore, for the successful operation of such a concept, it should be considered that people have the education and the awareness about waste separation. In addition to this proper source-separating equipment should be available such as a bio-waste bin and is accessible to everyone.

4.4.2 Determination and evaluation of food waste quantities

4.4.2.1 Total food waste

The waste composition analysis only highlights the composition of FW contained in bio-waste and the residual wastes. However, for developing decentralised concepts with mAD units the local available amounts on FW are required. An approximation of FW collected per LC inhabitant ($m_{FW\text{-}Inh}$; in kg/Inh & year) was determined using the INFA (2013) and EBL (2016) results obtained from analyses of bio-waste and residual waste compositions and the number of inhabitants in the respective waste collection area (Figure 22):

- FW contents ($c_{FW\text{-}BW}$; $c_{FW\text{-}RW}$):
  43.9% of bio-waste, 27.5% of residual waste (INFA, 2013)
- Mass of bio-waste and residual waste collected from EBL (m_{BW}; m_{RW}):
  16000 t bio-waste and 44000 t residual waste per year (EBL, 2018a)
- Inhabitants in the catchment area (n_{Cap}):
  216 253 (Statistikamt Nord 2015)

The FW collected from the inhabitants was calculated using Eq. 1:

$$FWpot = \frac{\left(c_{FW-BW} * \frac{m_{FW-BW}}{a} + c_{FW-RW} * \frac{m_{FW-RW}}{a}\right) * 1000}{cap} \left[\frac{kg\ FW}{cap * a}\right] \quad \text{Eq.1}$$

In line with the calculation above, the calculated amount of FW collected amounts to 87 kg FW per capita and year: Whereby 32 kg per capita and year was found in the bio-waste and 55 kg per capita and year in the residual waste.

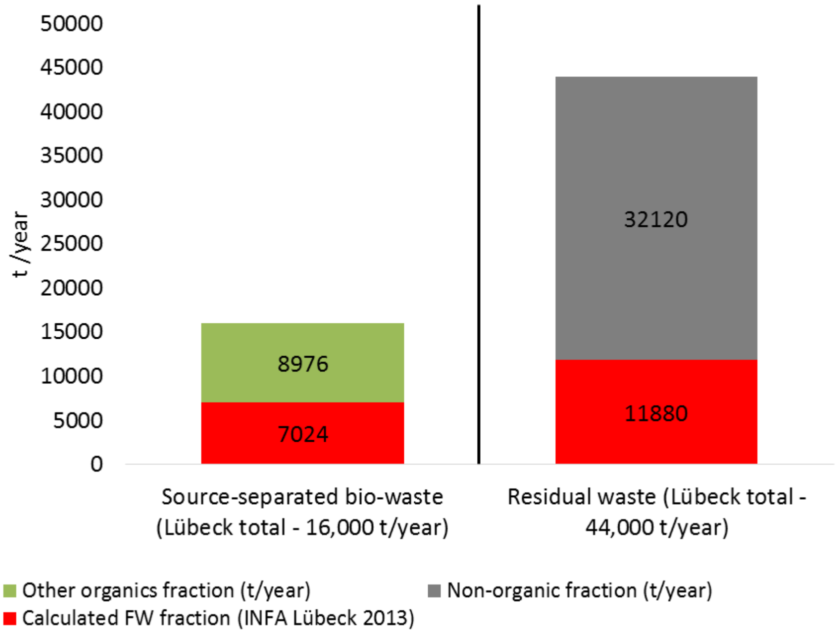


Figure 22: Source-separated bio-waste and residual waste collected by the waste authority of Lübeck including their shares of food waste

These results are similar to those of a fundamental German study. According to Kranert et al. (2012) 80 kg FW is generated per capita and year, whereby 60 kg are collected via biobin and residual waste bin.

4.4.2.2 Avoidable food waste

The results from the TUHH waste composition analyses (Chapter 4.3) are summarised in Figure 23 and compared with data according to Kranert et al. (2012). In contrast to the current study, Kranert distinguishes three avoidability classes. The additional class "Partially avoidable FW" was defined by Kranert et al. 2012 as "*generated because of different consumer habits (e.g. bread crusts, apple skins). This category also covers mixtures of avoidable and unavoidable waste (e.g. leftover food, canteen waste, etc.)".* For instance, some people consume potato and apple peels and bread crumbs, while others would rather discard them. In this study, such wastes were assigned to unavoidable waste. The definitions used for analyses for avoidable and unavoidable FW is summarised in Appendix Table 20.
Both studies reveal a high potential of avoidable FW. Based on this, the FW avoidance goal of the EU action plan "Closing the loop" of 50 % is achievable for the considered studies.

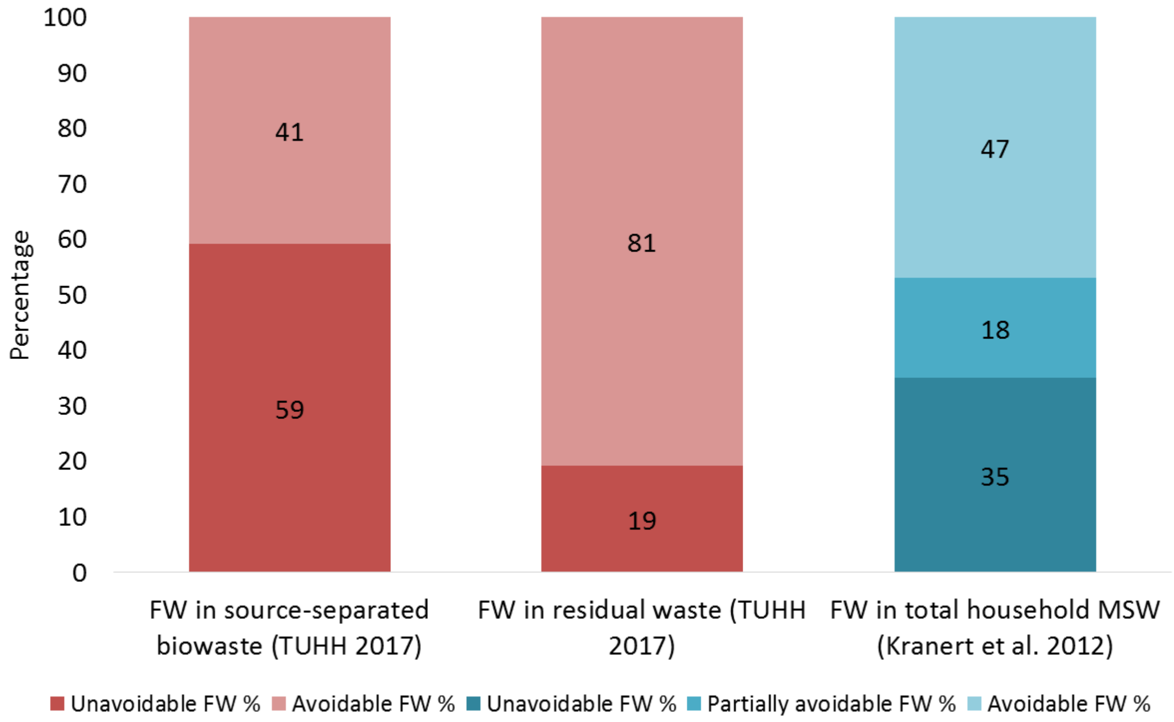


Figure 23: Proportions of food waste regarding their avoidability compared for two studies based on data from 2017 and data published (Kranert et al. 2012)

4.4.3 Considerations for decentralised systems

Based on the findings from the waste composition analyses certain aspects have to be considered for the design of an advanced decentralised bio-waste collection chain for the eco-settlement Lübeck-Flintenbreite:

- The high FW share in residual waste fraction (35%) suggests that a new collection system should enable the redirection from residual waste to the source separated bio-waste. This should be linked with redirections of other recyclables from the residual waste bin to the appropriate bins.
- The very high proportion of avoidable FW in residual waste and bio-waste shows that there is a high FW prevention potential. Advanced decentralised collection concepts should therefore contain tools for checking the waste composition and education for citizens (later study).
- The macro-impurity content in bio-waste is low and probably unproblematic for mAD.
- Further materials that can be used in the mAD contained in bio-waste and residual waste includes mainly tissues. The shares are low enough with respect to the demands of BioAbfV and therefore could be collected together with the kitchen waste. However, if used in a kitchen waste shredder tests should be performed to see if this process is possible. Since tissues commonly contain wet-strength media, their behaviour in mAD should be also tested (later study).
- The second compound of importance as a mAD co-substrate is green waste, which is to be expected due to its high proportion in the source-separated biobin, but not in the residual waste bin. The behaviour of green waste in the kitchen waste shredder was therefore tested (Chapter 5).
- Advanced waste composition analysis should include the aspect of avoidable FW fractions. If it is necessary to distinguish between animal- and plant based FW, this and further questions should be evaluated within the life-cycle-assessment work package.

In conclusion it is important to consider temporal and spatial variations when conducting waste composition analyses. Future analyses should therefore be set in context with results obtained from other studies to avoid misinterpretations.

The amount of FW produced in relation to inhabitants needs to be combined with mass of FW and inhabitant data, which can be found in various public available documents. It may also help to compare studies and evaluate plausibility and to get in contact with the data providers for specific explanations.

To design efficient decentralised collection systems data are needed. It is suggested to work with multiple data sources since it is not possible to generalise from single measurements. For the scenario development (Chapter 6) the following calculation ranges were worked out, based on results obtained and comparisons made with other studies:

- Collectable FW amount: 60-90 kg/inhabitant and year
- Macro-impurities in bio-waste: 1-5 % of bio-waste
- Long term goal for FW avoidance: 50 % of the currently collectable FW

All data refer to the household sector. The ranges may be upgraded based on future studies.

5. Application of a decentralised bio-waste shredding system in Lübeck-Flintenbreite

5.1 Purpose and work program

To design a decentralised bio-waste collection system for the eco-settlement Lübeck-Flintenbreite, it is necessary to test the already available infrastructure and to evaluate its suitability for an advanced decentralised bio-waste collection and valorisation concept. The key element is in this scenario is the available mAD unit which was designed for wet fermentation (Chapter 3.3). To valorise bio-waste with this specific mAD plant, it is necessary to pre-treat the bio-waste with in regards to reducing its particle size. This increases the efficiency of the conversion of organic material to biogas. Moreover, the mAD is intended to treat blackwater, with which the bio-waste has to be able to mix homogenously with. Another advantage of decreasing the particle size is that it improves the hygienisation of the substrate.

Particle size reduction can be performed by shredding the waste in the pre-treatment step of AD. In LF a technical shredding system is situated in the basement of the main building of close to the biogas plant, it is however yet to be used to treat bio-waste. Residents or those responsible are able access the shredder to dispose of their bio-waste via an opening located on the outside of the building. From here the disposed bio-waste material slides directly into the shredder where its size is reduced and is ready to be pumped into the mAD plant.

It is important to test the available waste shredding system for the generated waste in terms of operation by processing waste samples of the bio-waste collection (Chapter 4). Hence, the specific work goals of these shredding experiments can be summarised as follows:

1 **Testing the available shredding system regarding principal functionality**: To operate the system securely under variable working conditions and to describe the operation options.

2 **Investigating different bio-waste regarding the usability of the shredding system:** To find out which fractions can be handled by the unit and which cause problems; to describe the problems and suggest solutions.

3 **Characterising the shredding output regarding usability for mAD:** To provide data of output properties including particle size, bulk density, dry matter (DM), volatile solids (VS) and Biogas Potential (BGP21).

4 **Evaluating the shredding system regarding usability in a decentralised bio-waste valorisation concept:** To evaluate technical data (e.g. capacity, energy consumption, heat development) and the technical performance for the specific case of LF

To achieve these goals, samples of selected fractions from the bio-waste samples investigated in chapter 4 were tested. This includes the shredding itself as well as the determination of process parameters and the characteristics of the shredding output. Selected shredded samples were collected and stored under deep freezing conditions for future micro-impurity and nutrient-analysis which implies the connection to DST assessments.

5.2 Material and methods

5.2.1 Technical equipment

For the waste shredding procedure, the shredding system available at LF was used. It is an industrial meat grinder with a batch size between 120 and 130 litres. It can be operated under batch-mode or continuous conditions, resulting in a throughput of up to 2000 kg/hour. It was installed during the development phase of the eco-settlement in the year 2000 for the purpose of bio-waste shredding.

This section reviews the relevant technical features of this shredder with respect to usability for a decentralised bio-waste valorisation concept in LF. All data was provided by the manufacturer Kolbe 2017.

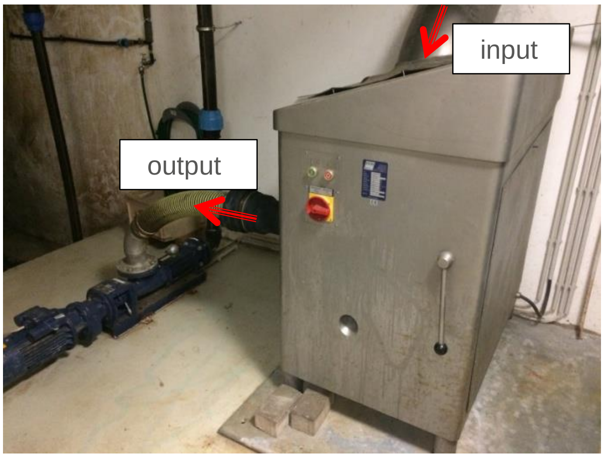


Figure 24: Shredder installed at the eco-settlement Lübeck-Flintenbreite (Photo: Oyedele 2017)

The equipment was originally designed to fulfil the requirements of medium-sized industrial meat-processing companies. It is a high-performance machine with a compact construction that is able to process fresh and frozen meat. Therefore, it was assumed that food waste and garden waste could be shredded as well.

The feeding screw, situated directly below the feeding orifice (Figure 24) transports the substrate to the cutting system. The cutting system (Figure 25) consists of several parts: one pre-cutting disc, two perforated discs and two cross-blades for cutting with a 130 mm diameter. The diameter of the holes in the first perforated disc is 13-mm; in the second one, the holes have a diameter of 3 mm. After the waste leaves the system the particle size should be less than 3 mm in size. All wastes which cannot be handled by the system would result in a blockage at one of the discs.

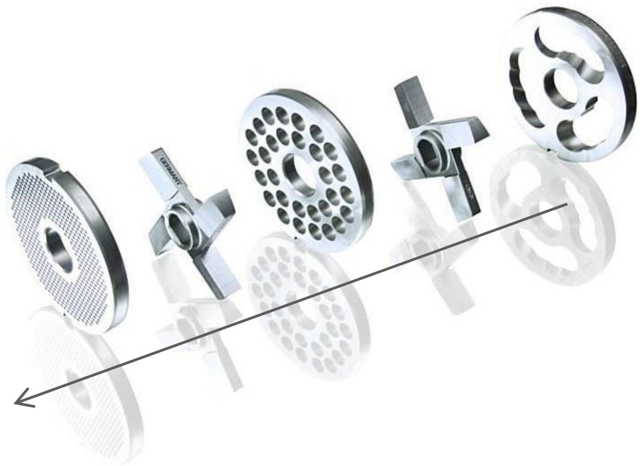


Figure 25: Configuration of cutting system used in the meat grinder (Kolbe 2018)

From the operational point of view, following parameters are relevant:

- The unit is fitted with an 11 kW main-drive motor
- The output performance is up to 2.000 kg/hr of shredded material (meat).

From the dimensions the following aspects are relevant:

- Regarding the external dimensions, the manufacturer reported 1010x1160x1380 mm (width, length, height), with a maximum filling height of 1155 mm. These dimensions are relevant to identify space requirements for the shredding operation.
- The dimensions of the cutting system housing are 130 mm of inner diameter and 270 mm of length. This represents a volume of approximately 3.5 litres for the whole cutting system, which

contains the perforated discs and the blades (Figure 25) and can be filled with compressed bio-waste. Thus, it is important to collect all the material after every test to avoid the loss of information and to allow clean operations without intermixing of samples.

5.2.2 Materials

The experiments were performed using the organic fraction of bio-waste which was received from the waste composition analysis described in chapter 4.
Three waste categories were selected to be shredded and analysed (Table 11). The first one comprised of garden waste with a particle size larger than 40 mm while the second one contained the garden waste with a particle size between 10 and 40 mm. Both fractions consisted of green waste organics only, and no woody materials were determined. The third sample included all food waste fractions mentioned in Table 11. The various FW fractions, identified and separated in chapter 4, were mixed to a homogeneous food waste sample. Some macro-impurities, including 2 collection bags, which could not be separated from the food waste, were included (see Figure 26, right).

Table 11: Samples of waste component analysis used for shredding experiments

Sample Number	Origin	Shredded fraction	Fractions numbers (from Table 7, Chapter 4)
Shred-sample 1	Bio-waste	Garden green >40mm	11
Shred-sample 2	Bio-waste	Garden green 10mm-40mm	26
Shred-sample 3	Bio-waste	All collected food waste[1]	1,2,3,4,8,10

[1] All collected FW-fractions, except "original packaged food, plant based" fraction number 6, because only 0,1 kg of this fraction was collected (Table 17 in Appendix)

Figure 26: Waste samples 1,2,3 (left to right) (Photo: Deegener, 2017)

With samples 1 and 2, the capability of the shredder regarding processing of garden waste, which is more rigid compared to FW, was tested. Furthermore, the performance regarding the different initial particle sizes was evaluated. Sample 3 investigated the usability of the soft FW, without packaging materials.
The experiments with samples 1-3 were carried out in December 2017.

5.2.3 Shredding procedure

The sample is placed inside of the feeding orifice of the shredder, the machine is switched on and after the shredding process the material is recovered. The material in the transportation section of the shredder required the attention users that were performing a real-time evaluation responding to any potential clogging of the cutting system. After each sample was processed, the cutting system was cleaned and prepared for the next batch. The process was repeated for each of the mentioned waste fractions.

5.2.4 Analytical methods

The following parameters were determined for the shredded outputs:

- Total Solids (TS), DIN EN 15934; double determination
- Volatile solids (VS), DIN EN 15169; double determination
- Estimated bulk density (weight measured, volume estimated)
- Biogas potential in 21 days (BGP21), VDI 4630; triple determination

Nutrient- and heavy metal content of the shredded material will also be determined, but provided in a future document (D3.3).

5.3 Results

5.3.1 Shredding experiments

The first fraction to be processed was the green garden waste with a particle size above 40mm (Sample 1, Figure 28, left). After the experiment was performed, three different outputs were identified: 1) material that remained in the transportation section (i.e. before the first disc); 2) material inside the cutting section; and 3) material that went throughout the whole process and was collected outside the machine (blended material). All the outputs were weighted.

The procedure was repeated for the green garden waste with a particle size between 10 and 40 mm (sample 2, Figure 27, middle). In this step no material remained in the transport section. Most output material could be assigned to the blended material; while only some remains were found inside the cutting system and in the empty spaces between the discs and blades, no blockages occurred. This suggests a better performance of the shredder, indicating that smaller garden waste particles are easier to be processed by the shredder than larger ones.

Finally, the food waste was shredded (sample 3, Figure 27, right). In this case, the shredder clogged and the highest output amount was found in the transport section. After stopping the test and recovering much of the sample, it was apparent that a plastic bag in the food waste was obstructing the process, followed by food particles that weren't transported to the blades. Most of the waste was found in either the transport or the cutting section of the machine. In order to clean the equipment, a water jet was required.

Figure 27: Obstruction found after processing garden waste (sample 1 left) in transport screw; Ground material sample 2 (green garden waste 10mm-40mm, middle); Blockage of FW (sample 3 right) in cutting section (Photos: Deegener 2017)

5.3.2 Characteristics of ground materials

From the valuable outputs of the ground material, the material properties were determined and presented in Table 12.

Table 12: Results of first shredding experiment

Fractions	Input / Output (blended material)	Bulk density [kg/L]	Bulk density increase [%]	TS [%]	VS [% of TS]	Biogas potential [NL/kg FM]	Biogas potential [NL/kg VS]
Shred-sample 1	Input	0.22	Not measured				
	Output	0.5	127	38.2	68.1	43	165
Shred-sample 2	Input	0.29	Not measured				
	Output	0.7	141	36.2	55.4	44	220
Shred-sample 3	Input	0.37	Not measured				
	Output	0.8	116	24.9	78.1	80	410

An increase of density observed in all of the three shredded samples highlights the capability of the device to reduce the particle size of the materials resulting in reduced volume. Total solids content of food waste is approximately 11% lower than green waste. However, volatile solid content is 10-23% higher. FW showed a higher biogas potential in comparison to the green waste. In Figure 33 (Appendix) the biogas production is shown. With 55 kg/d of FW and the biogas potential of 80 NL/kg FW 4400 NL Biogas can be produced. With a methane content of approximately 60%, 26kWh/d energy and approximately 10kWh/d electrical energy can be produced by the CHP.

5.3.3 Energy consumption

It is estimated that 55 kg/d of FW is produced by the 250 Inhabitants from LF. For this amount the shredder would require approximately 2 minutes to process this amount of FW, which sums up to an energy-consumption of 11 kW*0,0275 h= 0,30 kWh/d.

5.4 Considerations for decentralised systems

It has been found that some organic materials combined with macro-impurities cannot be easily processed by this shredder. Therefore, other technologies or previous treatment steps or control of the quality when collecting the bio-waste should be considered in order to obtain a blended material that can be pumped into the anaerobic digestion reactor. Modifications should be made to the current system in order to resolve the issue of shredding waste with plastic impurities and high particle size.

6. Scenarios for decentralised bio-waste collection for Lübeck-Flintenbreite

This chapter focuses on the definition of scenarios for the implementation of decentralised bio-waste management systems in LF. Two main scenarios, with several sub-scenarios were developed. Considering the constraints and opportunities identified in the previous parts, these new collection systems have to be implemented so that:

- They allow the improvement of source separation of bio-waste;
- They contribute to collect bio-waste with a very high quality (e.g. low macro-impurity rate)
- They enable a reduction of the environmental impact of the overall system, by reducing the transport distances and allowing the use of environmentally friendly collection vehicles

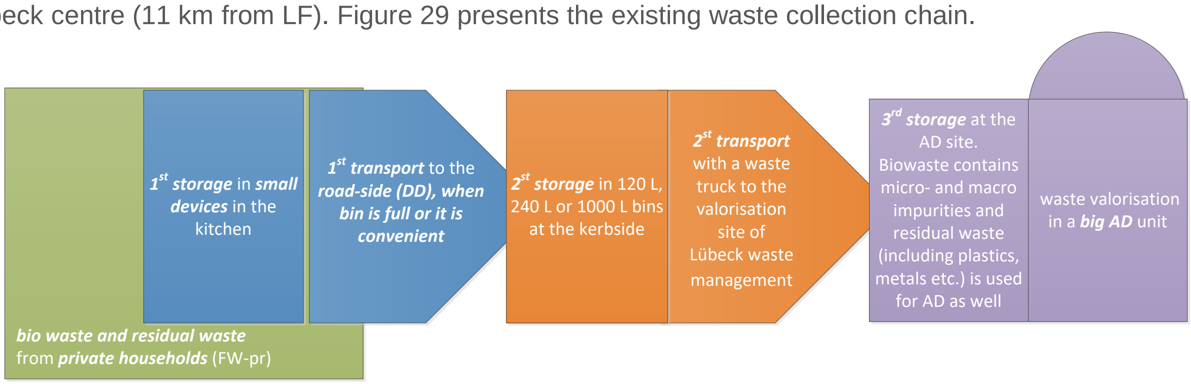
Bio-waste level	Bio-waste generator level	Bio-waste collector level	Bio-waste valorisation level

Figure 28: Principal stages of a bio-waste collection chain

The scenarios are based on the general bio-waste collection chain (Figure 28) introduced in detail in D3.5 and D3.7. The colours used in the scenario visualisations refer to the general levels of the waste collection chain.

6.1 Current system for waste collection

The existing system can be described as follows: the 81 households (about 250 inhabitants) usually have their own small FW-bins for source-separated collection, commonly stored inside the kitchen. Generally, it contains a (plastic) bag (compostable or non-compostable) for storage and to ease the transport to the second storage in the biobin outside the house (Figure 7). In this step, the waste is transferred to a nearby shared biobin of the size between 120 L and 240 L, depending on the housing structure (row houses, single family houses etc.). With a biweekly frequency the waste is collected by the cities' waste management company EBL and transferred to the centralised biogas plant around 10 km outside of Lübeck centre (11 km from LF). Figure 29 presents the existing waste collection chain.



Existing collection chain FW-pr 0:
FW from private households (250 inhabitants); unknown motivation; very small catchment area; low collection frequency; DD collection, vehicle transport; no co-substrate

Figure 29: Existing collection chain in Lübeck-Flintenbreite

6.2 New collection scenarios for Lübeck-Flintenbreite

The following scenarios describe options for new decentralised source-separated bio-waste collection schemes in LF. Each scenario includes the use of the existing mAD unit with a working volume of around 50 m^3 plus a headspace volume of 23 m^3 (Wendland 2009). Different waste amounts were assumed as shown in Table 13, e.g. the theoretical maximum potential. Those are based on the data of food waste quantities measured by INFA (2013) and Kranert et al. (2012). The bold marked amounts are the quantities of collected food waste of the LF inhabitants used for mAD.

Table 13: Framework for new waste collection scenario development

Quantities of FW [kg/(cap*a)]	Source-separated FW	Non-source separated FW	Total FW
Literature data for scenarios	32	55	87[1]
	19	43	62[2]
Scenario future waste reduction	**40**	0	40
Scenario theoretical maximum potential	**80**	0	80
Scenario medium source-separation efficiency	**40**	40	80

[1] INFA (2013)
[2] Kranert (2012)

It has to be considered that the mAD unit was designed to treat the blackwater from all households, (5L per capita and day or 1250 kg/d[1] and 1 % TS for 250 inhabitants; Wendland 2009) and that it has a maximum capacity of 10%. To increase the TS to the maximum capacity (10% TS), around 750 kg/d (approx. 275 t/yr) of FW (25% TS, see section 5.2) would be necessary. This quantity exceeds the amount of food waste available in LF even at a capture rate of 100% of food waste, meaning around 55 kg/d[2] of total FW in LF.
However, there are different options to fill this gap. While “alternative 1” described in scenario 1 includes lawn cuttings of the public areas of LF, “alternative 2” describes how many inhabitants, e.g. from the surrounding neighbourhood would be necessary to run the plant at full capacity.

Scenario 1: Door-to door food waste collection from private households and blackwater
This scenario includes 55 kg/d of FW and total collected blackwater of 1250 kg/d. The former value refers to the maximum source-separation potential for collected FW as mentioned in Table 13. The general scenario is displayed in Figure 30.

[1] For simplification, the density of both, FW and blackwater, was assumed to be 1 kg/L after shredding.
[2] 20 t/yr or 80 kg per capita and year

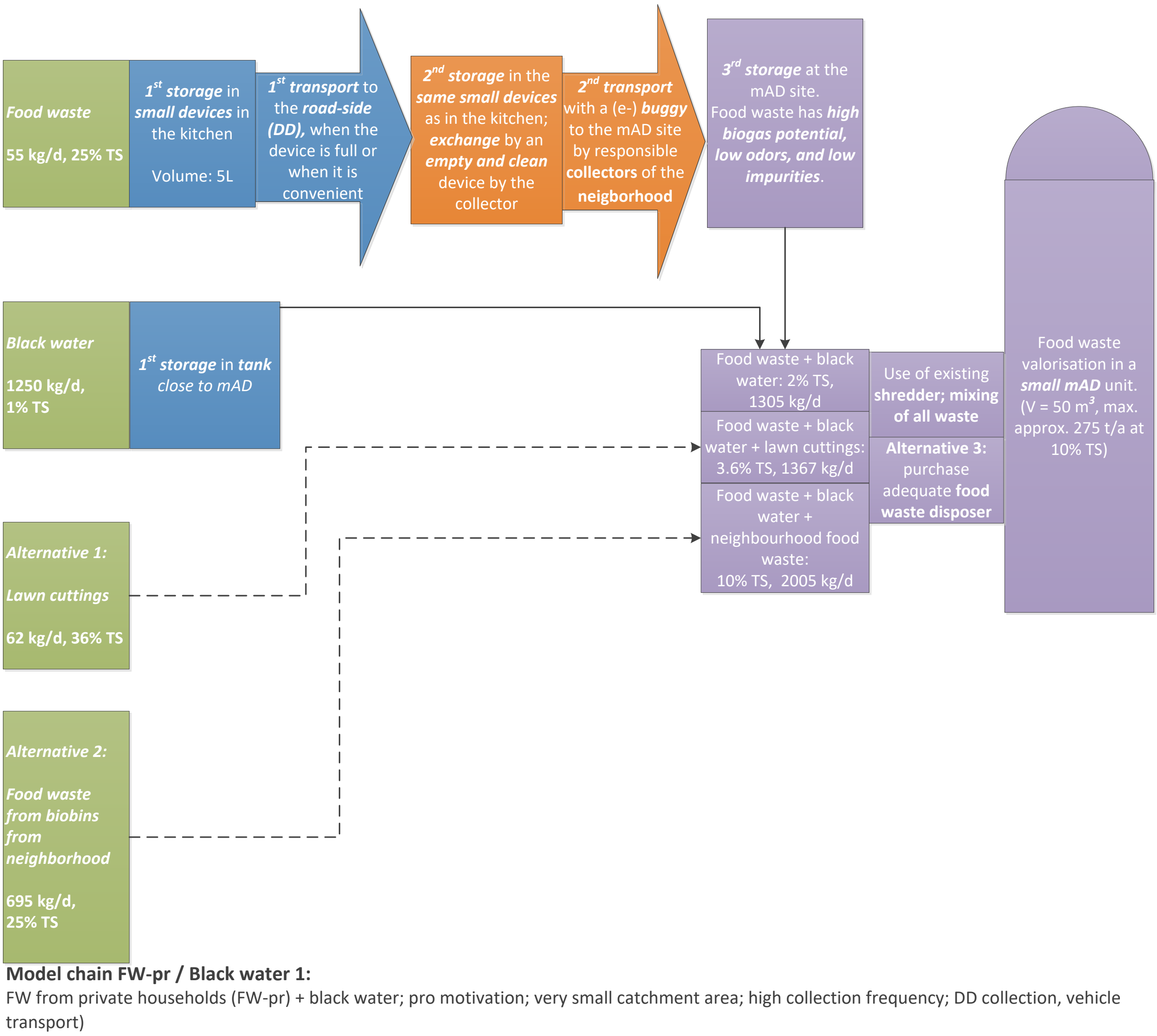


Figure 30: Scenarios for food waste collection from private households in connection with blackwater collection from vacuum toilets + actual shredding system and alternatives

Scenario 1 defines that the inhabitants possess small (5 L) FW-bins for FW disposal. The inhabitants can place them outside of the building if full or if they consider it needs to be emptied. However, recommendations are given to the inhabitants to put the buckets outside of their house at reasonable frequency, e.g not before it is half full or at least twice a week. This eases the collection of the 81 buckets since not all have to be collected and processed at the same day. Collection is performed daily and door-to-door (DD) by a collector who is elected by the inhabitants and responsible only for the settlement. To avoid bad odours, the buckets are replaced with a clean one upon collection, while the used buckets are cleaned by the collector. The bucket collection is conducted using an e-buggy, facilitating the transport of the waste to the mAD site. If every household puts its FW outside their house twice a week (from Monday until Friday) the collector would have to take care of an average of 32 buckets per day. This amount can be collected in one run.

The third FW storage unit is situated at the existing community shredder. The shredder can easily be fed via a lid. Since the collector is also responsible for screening the waste quality in terms of impurities, FW destined for the mAD will be of very high quality. Bad odours around the mAD facility are also marginal since FW is only stored for a short time before being introduced into the biogas plant.

Furthermore, the blackwater is treated in the mAD plant. Some of the blackwater is used when shredding the FW to ease grinding. Based on this feedstock, the TS content will be around 2%. This is well under the maximum capacity of the plant.

To increase the TS content of the feedstock and to increase the overall biogas production the following alternatives are described:

Sub-scenario 1.1: Addition of lawn cuttings

Lawn cuttings which occur in LF can be integrated into the available feedstock. The total lawn area is 26,500 m^2 with an estimated amount of lawn cuttings of 26.7 t/yr (1.0 kg/m^2 and year) (Hertel 2015). The lawn cuttings have a TS of 36% (Table 11) and their addition results in an increase of TS to 3.6%. The lawn cuttings will be stored with the FW next to the shredder. However, this amount is still not sufficient to run the mAD unit at full capacity. The FW collector would also be responsible to cut the lawn which would be done on a biweekly basis. However, growth rate has seasonal differences since most of the annual grass amount grows during spring and summer. To keep the TS at the same level throughout the year, a part of the lawn cuttings from spring and summer can be ensiled.

Sub-scenario 1.2: Addition of further food waste from households of the surrounding neighbourhood of Lübeck-Flintenbreite

To use the full capacity of the plant including all blackwater, the amount of FW needs to be increased. This can be achieved, if households of the surrounding neighbourhood of LF get involved. It is assumed, that source-separation in LF is still 100%.

To reach a TS content of 10% including blackwater and FW, approximately 700 kg/d of FW with a TS of 25% have to be added resulting in a total amount of 750 kg/d of FW and 1250 kg/d of blackwater. Assumptions for this alternative regarding the surrounding neighbourhood of LF were the following:

- waste collection will be done by the Lübeck waste management (EBL) and waste gets delivered to the mAD of LF
- source-separation efficiency is less than 100%, meaning some bio-waste gets disposed of into the residual bin and cannot be used for mAD
- varying motivation of the neighbourhood which is not attached to a new collection system in which a collector can screen the bio-waste regarding its quality.

The issue of varying motivation is shown in Figure 31, demonstrating the number of further inhabitants of the surrounding neighbourhood needed to run the mAD at full capacity as a function of their available food waste in the biobin. This can be related to their source-separation efficiency or the above mentioned FW reduction. Furthermore, it has to be taken into account that less bio-waste per capita and year may be available in the future due to the EU's target of 50% food waste reduction for the year 2030.

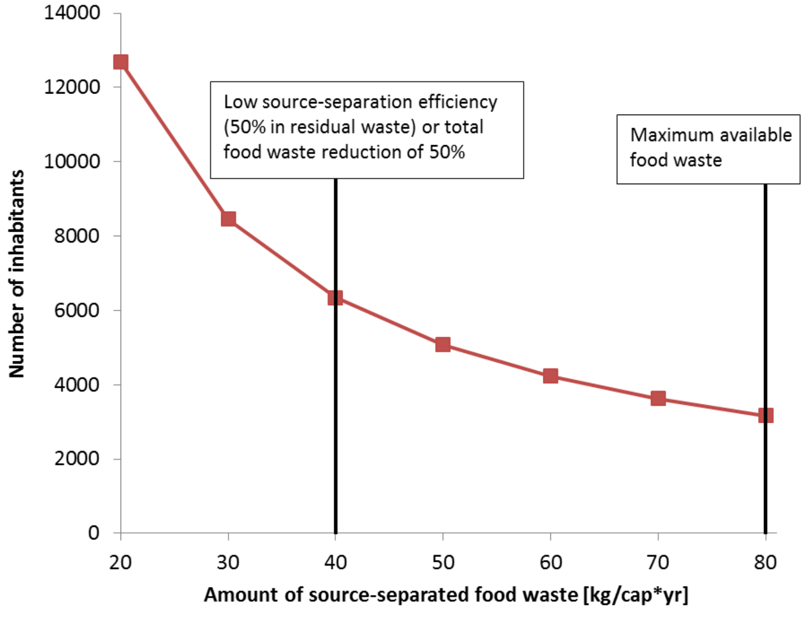


Figure 31: Number of inhabitants to run the mAD unit at full capacity as a function of their source-separation efficiency

The main conclusion of this scenario is that the available food waste in LF is insufficient to run the mAD plant at full capacity. Depending on the source-separation efficiency of the inhabitants of the surrounding neighbourhood of LF the waste of between 4000 and 12500 further inhabitants is needed.

Sub-scenario 1.3: Exchange of shredder with kitchen waste disposer
Additionally, to scenario 1, an efficient food waste disposer can be installed next to the mAD since the existing shredder assigned to LF has been found to be inappropriate when processing the available food waste. In terms of applicability, the dimensions of the disposer have to be chosen to treat at least 55 kg/d of food waste.

Scenario 2: Automatic food waste collection and blackwater
The major difference to scenario 1 is the automatic collection instead of a door-to-door system. The waste amounts are as described in scenario 1. Figure 32 shows the waste collection chain scenario.

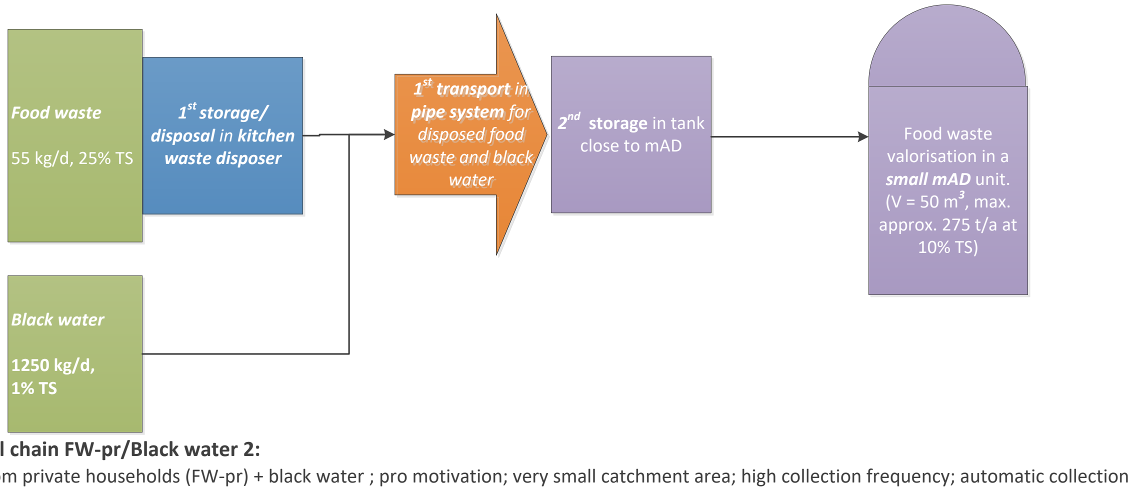


Figure 32: Scenarios for food waste collection from private households in connection with blackwater collection from vacuum toilets + new shredding system

Each household obtains a small kitchen waste disposer. The use of this device aims to improve the quality of FW and to be free of macro impurities. The ground FW from the kitchen waste disposer is then transported via a connected pipe system to a storage tank next to the mAD where it gets mixed with the blackwater. The feeding of the mAD unit is conducted as in scenario 1. Furthermore, the same additional substrates can be used to increase the capacity of the mAD plant. If the existing shredder is not supposed to be used anymore, a further substrate which has not to be ground could be used such as residue grease from restaurants.

6.3 Alternatives to the decentralised anaerobic digestion plant

Since legal regulations may prohibit the use of a mAD plant close to a residential area or citizens refuse to have one operated close-by, other decentralised valorisation units may be considered. One option may be a compactor to reduce the waste volume. By reducing the volume, more waste is able to fit into bins whereby smaller bins would most probably be sufficient. This saves costs for the inhabitants over the long term after amortisation of the acquisition of costs from the compactor and also reduces transport costs to the central AD unit of LC.
Further scenarios will be investigated in D3.7.

7. Conclusions and outlook

7.1 Conclusion

For LF and LC the geographical, demographical, legislative, and technical frame conditions were described and an historical overview on the specific situation for the development of the eco-settlement LF was given (Chapters 2 and 3). Bio-waste of LC is currently managed centralised by the waste management company EBL to which LF is also connected. Introducing a decentralised DECISIVE-system would have consequences on the current central waste management: a part of the source-separated bio-waste would be removed from the central system and be managed by LF. Therefore, all investigation and demonstration activities in this direction need to be discussed with the waste management company EBL before undertaking them. The same is true for the involvement of the LF settlement management and the citizens residing in LF. If a transition into an improved system is intended to be carried out, scenarios have to be found, which are beneficial to all involved parties. Analyses of such scenarios regarding advantages and disadvantages of different solutions including the current situation may support this process.

Guidance of planning regarding necessary modifications may be provided by results obtained from the waste composition analysis of bio-waste and residual waste, which was carried out in this study for LC. Similar to other German studies, it showed that most FW is contained in residual waste and additionally, that most of FW is avoidable. Inhabitants mostly use the biobins to collect garden waste (Chapter 4). However, it also contains a partial fraction of FW, which is less than that found in the residual waste. When emphasis is placed on FW collection in a new decentralised valorisation system, increased attention must be drawn to intensifying source-separation. By informing citizens about the benefits of improved source-separation of FW, the goal of capturing 100% of FW in the source-separated bio-waste can be achieved. To support this, collection systems have to be provided which simplify FW collection and increase convenience for the citizens. One option could be an FW disposer, installed in the household kitchen sink. A further option includes collection buckets for all waste fractions, which are designed with respect to expected waste amounts and available space. Furthermore, all waste types should be collected a single location in the household and not in varying locations. For LF this would include: 1) biobins; 2) plastics, metals and composites; 3) paper and cardboard; 4) glasses; 5) residual waste at one place, e.g. in the kitchen under the sink.
FW avoidance is a similar important issue that could be considered. A new collection system could eventually provide indirect support and improved source-separation behaviour could also lead to higher participation in food-related issues. Furthermore, a new collection system could include tools to measure the FW amounts from the individual households. On the waste fee bill, a comparison with minimum, average, and maximum of waste generation could be provided as a benchmark. Information on strategies for FW avoidance and the value lost when disposing food could be provided as well. Such individual waste reports could be conducted and provided by a caretaker of the neighbourhood responsible the decentralised waste collection.
Extensive infrastructure is available in LF to support a mAD for FW. The original design to treat blackwater including FW as a co-substrate has to be considered as well as the current situation of the settlement management. Two technical devices were evaluated for their suitability for starting a mAD involving FW. The available shredding system was tested using various source-separated bio-waste fractions. Furthermore, the concept of the mAD was evaluated based on the design conditions of the installed reactor, being wet fermentation with a maximum solids content of 10% TS, and a reactor treatment volume of 50m³ (Chapters 5 and 6). The performance of the shredder showed that it is possible to produce a substrate of suitable quality for wet-fermentation-mAD in terms of particle size, however, source-separated bio-waste inputs resulted partly in technical problems during shredding. To improve this, the option to modify the grinding process is suggested, but still to use the current installed shredder device. Another option is to use a more suitable aggregate designed for FW specifically. Several scenarios for the source-separated bio-waste collection for decentralised applications were developed and compared as basis for future local decisions in LF. The scenarios describe in detail the different stages in the collection system (i.e. collection, storage, transport and preparation until its utilisation in a

facility). Both scenarios described require the acquisition of further equipment. As an example, when shredding FW, the addition of blackwater could benefit the reduction of blockages. Furthermore, kitchen waste disposers could be installed in each kitchen or only one device as an alternative to the shredder. Calculations showed that using only the source-separated bio-waste of LF is insufficient to run the plant efficiently. It is therefore necessary to include additional sources of source-separated bio-waste, such as lawn cuttings which could be sourced from lawns within the settlement. Likewise, the Lübeck waste management EBL could support the plant with additional source-separated bio-waste sourced from neighbouring households.

7.2 Outlook

Before introducing a decentralised collection system in LF further studies are needed. Further investigations on the LF case therefore focus on following aspects:

Further waste composition analyses will be carried out with focus on LF wastes. Within DECISIVE it is planned to investigate the specific situation of LF and compare it with LC. When comparing investigations between the two it could be identified if the source-separation behaviour in LF is different to the average of the city. To be able to undertake this investigation however, it is necessary that a close cooperation with EBL be established and maintained. Furthermore, it is planned to carry out an investigation into an advanced decentralised collection system and to compare it with the current situation, e.g. regarding the source-separation and avoidance behaviour of citizens. The new collection system applied in LF is intended only for research purposes within the frame of DECISIVE.

Interviews with LF citizens shall be carried out in combination with a questionnaire which is currently being developed. The proposed interviews aim to provide information on current practices of LF inhabitants regarding to waste collection including their concerns, wishes and knowledge on waste issues, and their opinion on operating a mAD in LF. In this context it is planned to distinguish the survey into respective social settlement groups. Survey work will be supported by project partners from AU (Denmark), namely in the methodological approach.

Life cycle inventories (LCI) will be carried out by project partners from AU (Denmark) using collected and future results of LF which is suggested for this purpose. On the basis of LF a guideline for decentralised LCI will then be able to be developed. The planned works consist of two major parts. Firstly, "*micro-impurities in waste collection*" in the different collection systems shall be evaluated. For information on micro-impurities waste samples from source-separated bio-waste and residual waste collection from LF and LC, respectively, shall be analysed and if possible extended to different social groups. The following basic parameters including micro-pollutants are important and are planned to be determined: TS (% of FS), VS (% of TS), ash (% of TS), calorific value (MJ/kgTS), Macro-elements and nutrients - C, K, N, P (% of TS), Micro-pollutants - Cd, Cu, Co, Ni, Hg, Cr, Pb, Zn, As (% of TS). In the second part *"Comparing existing and new waste management situations"* centralised waste management systems will need to be compared to decentralised ones. In this instance LF and LC should be used as a case study to compare all of the relevant parameters. Some information on this can already be found in this report while additional data will be gathered within DECISIVE. This future work also aims to model different decentralised systems according to potential "business and system development scenarios".
Results gathered from these current and future investigations on LF and LC will be included in the DECISIVE-DST and are important for various assessment strategies.

8. Appendix

Table 14: Summary of storage data of bio-waste and residual waste items for Lübeck-Flintenbreite

Storage data, bio-waste and residual-waste

Item	Unit	Single Value	Range-min	Range-mean	Range-max	Source or Assumption/Calculation basis
Device unit: bin (volume)	L/unit		40	570	1100	Entsorgungsbetriebe Lübeck 2018b
Device unit: bin (cost)	€/unit		5.82	82.9	159.93	Entsorgungsbetriebe Lübeck 2018b
Device unit: bin (water demand cleaning)	L/unit	5.04[1]				Based on the amount of water consumed daily per household 126L/Capita * day (Schleich, J.; Hillenbrand T. (2007))
Device base area (above ground)	m²/device		2.52[2]	3.1	3.6	Study of Lübeck-Flintenbreite 2017 (GIS digitising: area of waste bins bay)
Storage time until transport to 3rd storage	days	14				Entsorgungsbetriebe Lübeck (2016)

1 Assuming that the cleaning is done every 14 days after emptying (Assuming 2% of daily water usage goes into cleaning of the bins) 126L/Capita*day * 2 persons per household = 252 L/household*day: therefore 2% * 252 = 5.04L

2 Vector digitising on QGIS using polygon, and determination of polygon area

Table 15: Transport data for the bio waste from the eco-settlement Lübeck-Flintenbreite to the waste management complex of the city of Lübeck

Transport data, source-separated bio-waste

Item	Unit	Single Value	Method	Source or Assumption/Calculation basis
Distance[1]	meter/transport	11,128	Estimation by digitising/path-routing on QGIS	Average distance from Lübeck-Flintenbreite to the mAD plant (Waste management center Lübeck) - one way (calculation with Quantum GIS)
Collected FW (from source-separated bio-waste bin) per inhabitant	Kg/inhabitant (semiweekly)	1.3	Calculation based on INFA (32 kg/capita*year)	INFA 2013
Specific distance[2]	meter / transport*kg FW (biweekly)	34.24	11,128 meters/transport divided by kg of FW in the residual waste. 1.3 kg of FW per inhabitant in the bio-waste every 2 weeks (INFA Lübeck)	one way based on calculation
Time[3]	min / transport	16	Assuming average truck speed of 43km/h: Time in minutes = distance (km)/speed(km/h) (*60).	Stadtreinigung Hamburg - Siechau 2016
Fuel demand[4]	L / km	0.7	Uniform fuel consumption rate for all trucks types (0.7L of diesel per km).	Stadtreinigung Hamburg - Siechau 2016
Fuel demand[5]	L / km*kg FW	0.002		Stadtreinigung Hamburg
Manpower demand[6A]	person hours / transport*kg FW	0.025	Duration of tour: 4 hour A team: 1 Driver, 1 Loader (Average of 29€/person * h)	Stadtreinigung Hamburg - Siechau 2016
Average salary (costs)[7A]	€/person month*kg FW	0.18	Side-loader trucks (One driver, one loader= 2 People), Labor cost/hour: Driver - 30.22€/h, Loader - 27.87€/h	Stadtreinigung Hamburg (Assuming salary basis for bio-waste collection personnel)
Collection point density[8]	cp/km^2	333	LF 0.054 km2 : 20 collection points = 333 collection points/km2	LF Inventory 2018: number of bio-waste bins locations/collection points)
Transport vehicle volume[9]	m^3 / vehicle	23.3 (side loader truck)	Conversion of Truck capacities from Tons to cubic meters (using Density of Bio-waste in Lübeck (INFA 2013) = $430kg/m^3$). Volume of truck: Mass (Kg)/Density(Kg/m^3).	EBL Lübeck (2018c)

[1] Estimation by digitising/path-routing on QGIS (one way distance). One way distance from the waste management center to Lübeck-Flintenbreite
[2] Distance - 11128 meters/transport divided by kg of FW in the bio- waste. Based on FW data calculated from INFA 2013, 1.3kg of FW per inhabitant in the residual waste every 2 weeks.
[3] Assuming average truck speed of 43km/h: Time in minutes = distance (km)/speed(km/h) (*60).
[4] Assuming a uniform fuel consumption rate for all trucks types (0.7L of diesel per km).
[5] Assuming a uniform fuel consumption rate for all trucks: 0.7 L/km * 1/(2.29 kg of FW * 250)
[6] Assuming the usage of side -loader trucks (One driver, one loaders). One working day = 8 hours; and 2 tours. The truck should be full, or the tour completed before returning to the waste treatment plant. Assuming one hour on the tour for Lübeck-Flintenbreite Flintenbreite (Assuming all bins are placed closest to the roadside as possible).
[7] Assumption: usage of side-loader trucks (One driver, one loaders), 2 people in a team. Labour cost/hour: Driver - 30.22€/h, Loader - 27.87€/h
[A] Side-loader trucks are applied in both residential areas and commercial areas, and can lift 40L - 1100L bins
[B] side-loader trucks (One driver, one loader). One working day = 8 hours; and 2 tours. The truck should be full, or the tour completed before returning to the waste treatment plant. Assuming one hour on the tour for Lübeck-Flintenbreite Flintenbreite (Assuming all bins are placed closest to the roadside as possible).
[8] The Flintenbreite settlement is 0.054 km2 : there are 20 collection points within this area. Result: 333 collection points/km2
[9] Conversion of Truck capacities from tonnes to cubic meters (using Density of Bio-waste in Lübeck according to TUHH 2017 = $430kg/m^3$). Volume of truck: Mass (Kg)/Density(Kg/m^3).

Table 16: Transport data for the residual waste from the eco-settlement Lübeck-Flintenbreite to the waste management complex of the city of Lübeck

Transport data, Residual waste

Item	Unit	Single Value	Method	Source or Assumption/Calculation basis
Distance[1]	meter / transport	11,128	Estimation by digitising/path-routing on QGIS	Average distance from Lübeck-Flintenbreite to the mAD plant (Waste management center Lübeck) - one way (calculation with Quantum GIS)
Collected FW (from residual waste bin) per inhabitant	Kg/ inhabitant (semiweekly)	2.29	Calculation based on INFA (55 kg/capita*year)	INFA 2013
Specific distance[2]	meter / transport*kg FW (biweekly)	19.4	11,128 meters/transport divided by kg of foodwaste in the residual waste. 2.29 kg of FW per inhabitant in the residual waste every 2 weeks (INFA Lübeck)	one way based on calculation
Time[3]	min / transport	16	Assuming average truck speed of 43km/h: Time in minutes = distance (km)/speed(km/h) (*60).	Stadtreinigung Hamburg - Siechau 2016
Fuel demand[4]	L / km	0.7	Uniform fuel consumption rate for all trucks types (0.7L of diesel per km).	Stadtreinigung Hamburg - Siechau 2016
Fuel demand[5]	L / km*kg FW	0.001	Uniform fuel consumption rate for all trucks types (0.7L of diesel per km). 4 hour tour for a team): A team = 1 Driver, 2 Loaders (Driver - 30.22€/h, Loader - 27.87€/h)	Stadtreinigung Hamburg
Manpower demand[6A]	person hours / transport*kg FW	0.01		Stadtreinigung Hamburg - Siechau 2016
Average salary (costs)[7A]	€/person month*kg FW	0.25	usage of rear-loader trucks (One driver, two loaders), 3 people in a team. Labour cost/hour: Driver - 30.22€/h, Loader - 27.87€/h	Stadtreinigung Hamburg (Assuming Salary basis for biowaste collection personnel)
Collection point density[8]	cp/km²	333	LF 0.054 km2 : 20 collection points = 333 collection points/km2	LF Inventory 2018: number of bio-waste bins locations/collection points)
Transport vehicle volume[9]	m³ / vehicle	43.5	Conversion of Truck capacities from Tonnes to cubic meters (using Density of Bio-waste in Lübeck according to TUHH (2017) = 230kg/m³). Volume of truck: Mass (Kg)/Density(Kg/m³).	EBL Lübeck (2018c)

[1] Estimation by digitising/path-routing on QGIS (one way distance). One way distance from the waste management center to Lübeck-Flintenbreite

[2] Distance - 11128 meters/transport divided by kg of FW in the residual waste. Based on FW data calculated from INFA 2013, 2.29kg of FW per inhabitant in the residual waste every 2 weeks.

[3] Assuming average truck speed of 43km/h: Time in minutes = distance (km)/speed(km/h) (*60).

[4] Assuming a uniform fuel consumption rate for all trucks types (0.7L of diesel per km).

[5] Assuming a uniform fuel consumption rate for all trucks: 0.7 L/km * 1/(2.79 kg of FW * 250)

[6] Assuming the usage of rear-loader trucks (One driver, two loaders). One working day = 8 hours; and 2 tours. The truck should be full, or the tour completed before returning to the waste treatment plant. Assuming one hour on the tour for Lübeck-Flintenbreite Flintenbreite (Assuming all bins are placed closest to the roadside as possible).

[7] Assumption: usage of rear-loader trucks (One driver, two loaders), 3 people in a team. Labour cost/hour: Driver - 30.22€/h, Loader - 27.87€/h (Average = 29.05 €/h).

[B] Rear-loader trucks are applied in both residential areas and commercial areas, and can lift 40L - 1100L bins

[9] Conversion of truck capacities from tons to cubic meters (using Density of Bio-waste in Lübeck according to TUHH (2017) = 230kg/m³). Volume of truck: Mass (Kg)/Density(Kg/m³).

Table 17: Results of waste component analysis of source separated bio-waste from central waste management facility of Lübeck (December 2017)

Category no.	Category type	Fraction no.	Fraction type	Weight (Kg)	wet (w/w)%
> 40 mm					
1	Food waste – Unavoidable FW	1	Preparation remains (animal based)	0.28	0.13
		2	Preparation remains (plant based)	8.06	3.80
	Food waste – Avoidable processed FW	3	Leftovers (animal based)	1.32	0.62
		4	Leftovers (plant based)	2.62	1.23
		5	Original packaged food (animal based)	0.00	0.00
		6	Original packaged food (plant based)	0.10	0.05
		7	Opened packaged food (animal based)	0.00	0.00
		8	Opened packaged food (plant based)	0.16	0.08
	Food waste – Avoidable unprocessed FW	9	Unpacked original food (animal based)	0.00	0.00
		10	Unpacked original food (plant based)	1.38	0.65
2	Green and woody waste	11	Garden organics (green waste)	52.28	24.63
		12	Garden organics (woody waste)	14.80	6.97
	Wood waste	13	Wood waste (dry)	1.64	0.77
3	Glass	14	Glass	0.00	0.00
4	Paper	15	Paper/cardboard	2.44	1.15
		16	Tissue	1.50	0.71
		17	Other paper	1.74	0.82
		18	Paperbags	0.00	0.00
5	Plastic	19	Plastic	0.86	0.41
		20	Plasticbags	0.36	0.17
		21	Biodegradable plastic	0.36	0.17
6	Metals	22	Metal	0.04	0.02
7	Electronic & hazardous waste	23	Batteries, household chemicals, fluorescent light bulbs, paint and small electronic equipment	0.00	0.00
8	Non-identifiable waste	24	Non-identifiable waste	0.98	0.46
10-40 mm					
9	Foodwaste	25	Foodwaste (non specified)	1.3	0.6
10	Green - and woody waste	26	Garden organics (woody waste)	91.02	42.9
		27	Garden organics (green waste)	0.62	0.3
	Wood waste	28	Wood waste (dry)	0.00	0.0
11	Paper	29	Paper/cardboard	0.10	0.0
12	Non-identifiable waste	30	Non-identifiable waste	0.22	0.1
< 10 mm					
13	Non-specific waste	31	liquid	0.0	0.0
14		32	solid	28.6	13.2

DECISIVE

Table 18: Results of waste component analysis of residual waste from central waste management facility of Lübeck (December 2017)

Category no.	Category type		Fraction no.	Fraction type	Weight (Kg)	wet (w/w)%
> 40 mm						
1	Food waste	Unavoidable FW	1	Preparation remains (animal based)	0.22	0.14
			2	Preparation remains (plant based)	7.20	4.67
		Avoidable processed FW	3	Leftovers (animal based)	0.62	0.40
			4	Leftovers (plant based)	17.04	11.05
			5	Original packaged food (animal based)	0.78	0.51
			6	Original packaged food (plant based)	1.42	0.92
			7	Opened packaged food (animal based)	0.44	0.29
			8	Opened packaged food (plant based)	8.46	5.49
		Avoidable unprocessed FW	9	Unpacked original food (animal based)	0.00	0.00
			10	Unpacked original food (plant based)	2.52	1.63
2	Green and woody waste		11	Garden organics (green waste)	0.80	0.52
			12	Garden organics (woody waste)	0.00	0.00
	Wood waste		13	Wood waste (dry)	5.14	3.33
3	Glass		14	Glass	4.08	2.65
4	Paper		15	Paper/cardboard	25.66	16.64
			16	Tissue	6.96	4.51
			17	Other paper	0.00	0.00
			18	Paperbags	0.00	0.00
5	Plastic		19	Plastic	11.12	7.21
			20	Plasticbags	7.10	4.61
			21	Biodegradable plastic	0.00	0.00
6	Metals		22	Metal	7.60	4.93
7	Electronic & hazardous waste		23	Batteries, household chemicals, fluorescent light bulbs, paint and small electronic equipment	0.00	0.00
8	Non-identifiable waste		24	Non-identifiable waste	15.76	10.22
10-40 mm						
9	Foodwaste		25	Foodwaste (non specified)	15.93	10.3
10	Green - and woody waste		26	Garden organics (woody waste)	0.29	0.2
			27	Garden organics (green waste)	0.00	0.0
	Wood waste		28	Wood waste (dry)	0.00	0.0
11	Paper		29	Paper/cardboard	4.39	2.8
12	Non-identifiable waste		30	Non-identifiable waste	1.62	1.1
<10 mm						
13	Non-specific waste		31	liquid	0.0	0.0
14			32	solid	9.0	5.9

Table 19: Classification of Municipal Solid Waste; in preparation for D 3.7

<table>
<tr><th colspan="9">Municipal solid waste (MSW)</th></tr>
<tr><th colspan="5">Residual waste bin</th><th colspan="4">Bio-waste bin</th></tr>
<tr><td colspan="3">Bio-waste (non-source separated)</td><td colspan="2" rowspan="2">Other waste</td><td colspan="3">Bio-Waste (source separated)</td><td rowspan="2">Macro-Impurities</td></tr>
<tr><td>FW</td><td>GW</td><td>WW</td><td>FW</td><td>GW</td><td>WW</td></tr>
<tr><td></td><td></td><td></td><td>Other Recyclables (plastic, paper etc.)</td><td>Non-identifiable waste fractions</td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td colspan="2"></td><td></td><td></td><td></td><td></td></tr>
</table>

Table 20: Summary of food waste definitions in different studies (Kranert et al.2012 and TUHH 2017)

		Description				
		Unavoidable FW	Partially Avoidable FW	Aviodable FW	Avoidable processed FW	Avoidable unprocessed FW
Definition	Kranert et al. 2012	"usually arises when food is being prepared and is discarded. This mainly encompasses both non-edible constituents (e.g. bones, banana peels or the like) and edible ones (e.g. potato peels)"	"generated because of different consumer habits (e.g. bread crusts, apple skins). This category also covers mixtures of avoidable and unavoidable waste (e.g. leftover food, canteen waste, etc.)"	"usually arises when food is being prepared and is discarded. This mainly encompasses both non-edible constituents (e.g. bones, banana peels or the like) and edible ones (e.g. potato peels)"		
	TUHH BIEM, 2017	Preparation remains (animal and plant based): these are residues produced from the groceries while food is being prepared like vegetable clippings and fat from raw meat			Leftovers (animal and plant based): leftovers are remnants from cooked food which the consumer leaves behind. Original packaged food (plant and animal based): this is food that has been prepared, packed and ready to eat, but not touched, e.g cooked rice, noodles, salads, meat. Opened packaged food (animal and plant based): this is food that has been prepared, packed and ready to eat, and has been partly eaten e.g. noodles to go	Unpacked original food (plant and animal based):this is uncooked food still contained in its original packaging, like canned peas, sealed sardines

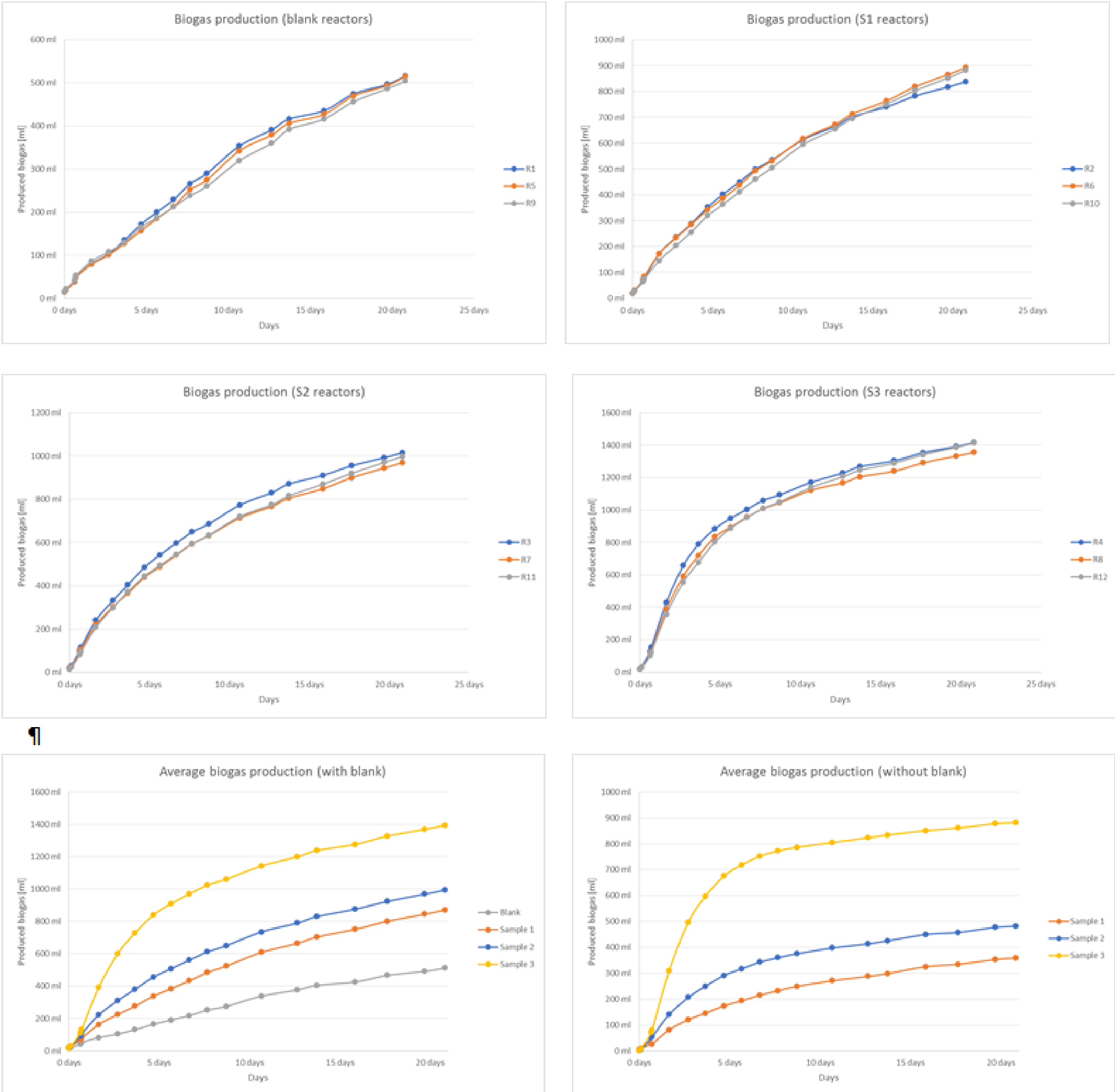


Figure 33: Summarised biogas production of BGP21-tests for shredded samples (1,2,3 from Chapter 5)

Sample 1: green garden waste >40mm; Sample 2: green garden waste 10-40 mm; Sample 3: source-separated FW

9. References

Adwiraah, H. (2015) *Bioressourceninventur-Analyse von Stoffströmen zur Bestimmung urbaner Biomassepotenziale in einem Geoinformationssystem (GIS)*, Ingenieurgruppe RUK GmbH, Stuttgart.

DECISIVE (2018) *Official DECISIVE Project website* [Online], DECISIVE. Available at http://www.decisive2020.eu/ (Accessed 13 February 2018).

Deutsche Bundesregierung (Editor) (2017): Verordnung über die Bewirtschaftung von gewerblichen Siedlungsabfällen und von bestimmten Bau- und Abbruchabfällen (Gewerbeabfallverordnung - GewAbfV). GewAbfV. Available online at https://www.gesetze-im-internet.de/gewabfv_2017/GewAbfV.pdf, checked on 2/26/2018.

Deutsche Bundesregierung (Editor) (2012): Gesetz zur Förderung der Kreislaufwirtschaft und Sicherung der umweltverträglichen Bewirtschaftung von Abfällen (Kreislaufwirtschaftsgesetz - KrWG). KrWG, revised 2017. Available online at https://www.gesetze-im-internet.de/krwg/KrWG.pdf, checked on 2/26/2018.

Deutsche Bundesregierung (Editor) (1998): Verordnung über die Verwertung von Bioabfällen auf landwirtschaftlich, forstwirtschaftlich und gärtnerisch genutzten Böden (Bioabfallverordnung - BioAbfV). BioAbfV, revised 2017. Available online at https://www.gesetze-im-internet.de/bioabfv/BioAbfV.pdf, checked on 11/22/2016.

EBL Lübeck (2018a) *Lübeck Entsorgungsbetriebe* [Online], EBL Lübeck. Available at http://www.entsorgung.luebeck.de/ueber_uns/daten_zahlen_fakten/index.html (Accessed 23 February 2018).

EBL Lübeck (2018b) *Lübeck Entsorgungsbetriebe* [Online], EBL Lübeck. Available at http://www.entsorgung.luebeck.de/privatkunden/restabfall/behaelter_und_gebuehren.html (Accessed 23 February 2018).

EBL Lübeck (2018c) Lübeck Entsorgungsbetriebe [Online], EBL Lübeck. Available at http://www.entsorgung.luebeck.de/ueber_uns/unsere_anlagen/kfz_werkstatt.html

EBL Lübeck (2018d) Lübeck Entsorgungsbetriebe [Online], EBL Lübeck. Available at http://entsorgung.luebeck.de/ueber_uns/aktuelles/news/2016_09_21_behaelterinventarisierung.html

EBL Lübeck (2017a) *Lübeck Entsorgungsbetriebe* [Online], EBL Lübeck. Available at http://entsorgung.luebeck.de/ueber_uns/unsere_anlagen/biomassewerk.html (Accessed 27 November 2017).

EBL Lübeck (2017b) *Lübeck Entsorgungsbetriebe* [Online], EBL Lübeck. Available at http://entsorgung.luebeck.de/ueber_uns/unsere_anlagen/mba.html (Accessed 27 November 2017).

EBL Lübeck (2017c) *Lübeck Entsorgungsbetriebe* [Online], EBL Lübeck. Available at http://entsorgung.luebeck.de/privatkunden/bioabfall/bioabfallsack.html (Accessed 27 November 2017).

EBL Lübeck (2017d) *Lübeck Entsorgungsbetriebe* [Online], EBL Lübeck. Available at http://www.entsorgung.luebeck.de/files/Flyer/infoblatt_abfalltrennung_web.pdf (Accessed 27 November 2017).

EBL Lübeck (2016): Abfallwirtschaftszentrum Lübeck. Neue Wege in der Abfallwirtschaft. Available online at http://entsorgung.luebeck.de/files/Flyer/broschuere_abfallwirtschaftszentrum.pdf, checked on 2/26/2018.

The European Comission (Editor) (2014): COMMISSION DECISION of 18 December 2014 (2014/955/EU) amending Decision 2000/532/EC on the list of waste pursuant to Directive 2008/98/EC of the European Parliament and of the Council.

Entsorgungszentrum Lübeck (2018). Available online at http://www.entsorgungszentrum-luebeck.de/index.html (Accessed 23 February 2018).

EWC (2015) *Guidance on using the European Waste Catalogue (EWC) to code waste* [Online], Scottish Environment Protection Agency. Available at https://www.sepa.org.uk/media/163421/ewc_guidance.pdf (Accessed 23 February 2018).

DECISIVE

Flintenbreite Lübeck *Flintenbreite Lübeck* [Online], Friedrich Schütt + Sohn Baugesellschaft mbH & Co. KG. Available at http://www.flintenbreite.de/ (Accessed 13 February 2018).

Geiger, R. (1954) 'Klassifikation der klimate nach W. Köppen', *Landolt-Börnstein, Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, alte Serie Vol*, vol. 3.

Hansestadt Lübeck (2018a) *Official website of the Hanseatic city of Lübeck* [Online]. Available at http://www.luebeck.de/ (Accessed 13 February 2018).

Hansestadt Lübeck (2018b) *Official city quarter of the Hanseatic city of Lübeck* [Online]. Available at http://www.luebeck.de/lvw_docs/forms/3/3_327_33/OKP_Karte_L_beck.pdf (Accessed 13 February 2018).

Hansestadt Lübeck (2014a): Abfallwirtschaftsgebührensatzung - AbfWGebS: Satzung der Hansestadt Lübeck über die Erhebung von Gebühren für die öffentliche Abfallwirtschaft in der Hansestadt Lübeck vom 30.11.2016. AbfWGebS. Available online at http://entsorgung.luebeck.de/files/Satzungen/gebuehrensatzung_abfall_ebl.pdf, checked on 2/26/2018.

Hansestadt Lübeck (2014b): Abfallwirtschaftssatzung- AbfWS. Satzung der Hansestadt Lübeck über die Abfallwirtschaft (Abfallwirtschaftssatzung-AbfWS) in der Hansestadt Lübeck vom 30.11.2016. Available online at http://www.entsorgung.luebeck.de/files/Satzungen/satzung_abfallwirtschaft_ebl.pdf, checked on 2/26/2018.

Hansestadt Lübeck (1999): Abfallwirtschaftsgesetz für das Land Schleswig-Holstein (Landesabfallwirtschaftsgesetz - LAbfWG) in der Fassung der Bekanntmachung vom 18.1.1999. LAbfWG, revised 2018. Available online at http://www.gesetze-rechtsprechung.sh.juris.de/jportal/?quelle=jlink&query=AbfWG+SH&psml=bsshoprod.psml&max=true&aiz=true, checked on 2/23/2018.

Hertel, S., Navarro, P., Deegener, S. and Körner, I. (2015) 'Biogas and nutrients from blackwater, lawn cuttings and grease trap residues-experiments for Hamburg's Jenfelder Au district', *Energy, Sustainability and Society*, vol. 5, no. 1, p. 29.

INFA (2018): Institut für Abfall, Abwasser und Infrastruktur-Management GmbH. Available online at https://www.infa.de/, checked on 2/26/2018.

Kolbe (2018): Kolbe foodtec. Paul KOLBE GmbH, D - 89275 Elchingen. Available online at https://www.kolbe-foodtec.com/, checked on 2/26/2018.

Körner, I. (2015): Civilization Biorefineries. In Ashok Pandey, Christian Larroche, K. Madhavan Nampoothiri, Mohammad Taherzadeh, Rainer Höfer (Eds.): Industrial Biorefineries and White Biotechnology. Amsterdam, Netherlands: Elsevier Ltd, pp. 295–340.

Körner, I.; Adwiraah, H.; Bade, O. (2009): Energetische und stoffliche Nutzung organischer Abfälle der SRH. Erstellung und Bewertung denkbarer Nutzungspfade. Edited by Martin Kaltschmitt. IUE: Institut für Umwelttechnik und Energiewirtschaft und JOMA Umwelt- und Beratungsgesellschaft mbH (1-04.769V). Available online at https://www.tuhh.de/forschung/fobe/2010/a1998.1-04/FB07_ForschProjekt_1284380662241.html

Kranert, M.; Hafner, G.; Barabosz, J.; Schuller, H.; Leverenz, D.; Kölbig, A. (2012): Ermittlung der weggeworfenen Lebensmittelmengen und Vorschläge zur Verminderung der Wegwerfrate bei Lebensmitteln in Deutschland. University Stuttgart, Institute for Sanitary Engineering, Water Quality and Solid Waste Management (ISWA); University of Natural Resources and Life Sciences (BOKU), Institute for Waste Management.

LfULG (2014): Sächsische Sortierrichlinie 2014. Sächsisches Landesamt für Umwelt, Landwirtschaft und Geologie. Available online at https://publikationen.sachsen.de/bdb/artikel/23865/documents/39943, checked on 1/31/2018.

LLUR (2015): Abfallbilanz 2015. Siedlungsabfälle. Landesamt für Landwirtschaft, Umwelt und ländliche Räume des Landes Schleswig-Holstein. Available online at https://www.umweltdaten.landsh.de/nuis/upool/gesamt/abfall/abfall_2015.pdf, checked on 2/23/2018.

Oldenburg, M. (2015) *Die ökologische Wohnsiedlung Flintenbreite, Lübeck* [Online], OtterWasser GmbH. Available at http://www.woche-der-umwelt.de/media/31050611220875b1.pdf (Accessed 22 October 2017).

OpenStreetMap contributors (2017) *Planet OSM* [Online]. Available at https://planet.openstreetmap.org/ (Accessed 23 February 2018).

OpenStreetMap contributors and Geofabrik GmbH (2018) *Germany* [Online]. Available at http://download.geofabrik.de/europe/germany.html (Accessed 12 January 2018).

Schleich, J.; Hillenbrand T. (2007): Working Paper Sustainability and Innovation. Determinants of Residential Water Demand in Germany. Edited by ISI Fraunhofer Institute Systems and Innovation Research (3). Available online at http://www.isi.fraunhofer.de/isi-wAssets/docs/e-x/working-papers-sustainability-and-innovation/working-paper_water-demand_final_02.pdf, checked on 2/26/2018.

Statistikamt Nord (2018): Datenanzeige für Lübeck, Hansestadt. Available online at http://region.statistik-nord.de/detail/10000000000000/1/0/358/, checked on 2/26/2018.

Veolia Umweltservice GmbH (2018): Official Webpage. Available online at http://www.veolia-umweltservice.de, checked on 2/26/2018.

Wendland, Claudia; Otterpohl, Ralf; Kaltschmitt, Martin (2008): Anaerobic digestion of blackwater and kitchen refuse. Hamburg, Hamburg, Hamburg: Ges. zur Förderung und Entwicklung der Umwelttechnologien an der Techn. Univ; Techn. Univ. Hamburg-Harburg (Hamburger Berichte zur Siedlungswasserwirtschaft, 66).

Contact

PD Dr.-Ing. habil. Ina Körner

Hamburg University of Technology;
Institute of Wastewater Management & Water Protection
BIORESOURCE MANAGEMENT GROUP (BIEM)

Eissendorfer Str. 42,
21073 Hamburg, Germany

Tel.: 0049 40 42878 3154
Fax.: 0049 40 42878 2684
i.koerner@tuhh.de
www.tuhh.de/aww