China Integrated Waste Management NAMA

Life Cycle Assessment of Waste Management in Bengbu, PR China

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List of Content

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Preface

This report summarizes the life cycle assessment (LCA) of the waste management system in Bengbu, PR China. The appendix contains the detailed documentation of the LCA-modelling.

The work was conducted between December 2019 and January 2021. The work was affected and delayed by the Coivd-19 pandemic. However, the outcome meets high international standards for LCA-modelling of waste management systems.

The work is part of the National Appropriate Mitigation Actions (NAMA) project involving collaboration between several Chinese authorities and GIZ.

We appreciate the hospitality and cooperation of the Housing and Urban-Rural Development Bureau of Bengbu City, in particular Mrs. Zhao Ying and Mr. Li Yue.

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Summary

This report has been prepared by Beijing Normal University, Beijing, PR China and Technical University of Denmark, Kongens Lyngby, Denmark in collaboration with the Housing and Urban-Rural Development Bureau of Bengbu City and GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit), Beijing under the GIZ contract number 81247604. The report should be cited as: Zhao, Y., Chang, H.M., Damgaard, A., Bisinella, V., Christensen, T.H. (2021): Life cycle assessment of waste management in Bengbu, PR China. GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit), Beijing. The report contains 60 pages and an appendix with 47 pages.

Introduction

Solid waste management is changing rapidly these years in China, moving away from landfills and increasing treatment and recycling of waste. Environmental considerations play a significant role in this change, but also aspects about resources, space and economy are important. Life cycle assessment (LCA) is an established method being able to quantify the potential environmental impacts of waste management. LCA has been used in waste management in addressing many aspects and in many countries during the last two decades. LCA quantifies a range of impacts and identifies where environmental loads and savings take place within the waste management system. Thus, LCA is a helpful tool in quantifying environmental progress within waste management and in assessing potential further improvements to be considered in the future.

This report quantifies by stringent methods the environmental impacts of waste management in the City of Bengbu, PR China. The City of Bengbu is located in the north of Anhui Province (longitude of 116°45'-118°04'E; latitude of 32°43''-33°30'N). The study covers waste generated in the four districts of Bengbu City: Bengshan District, Yuhui District, Huai Shang District, and Longzihu District covering 613 square kilometres and 1 150 000 people in total.

The LCA covers the period 2015-2035, divided into four time periods representing the actual development in the waste management for the city: 2015-2017 representing the “BASELINE” (prior to the start of the China IWM NSP), 2018-2019 representing the “CURRENT” municipal solid waste (MSW) system, 2020-2025 representing the “PLANNED” MSW system as expected within the 5-year plan. “FUTURE” is a hypothetical future MSW system with focus on further improvement in the environmental profile of the Bengbu MSW system, with a period of 2025-2035. These potential improvements considered in the FUTURE time period do not necessarily reflect the views of Bengbu City nor GIZ: they have been introduced to illustrate how ideas about waste management can be assessed in a quantitative way as part of a planning process and to illustrate how much room for improvement could be available from an environmental point of view.

Data on the Bengbu waste management system has been collected on location to the extent possible. Existing plans have been included. The three first time periods considered – BASELINE, CURRENT and PLANNED – thus have been modelled as closely to the actual situation as possible, while in the FUTURE time period we have quantified the environmental impacts of further developments that potentially could be considered without paying attention to actual capacities of existing facilities.

The LCA-modelling quantifies the flows of waste, materials and substances through the waste management system, while simultaneously keeping an account of exchanges of materials and energy needed to operate the waste management system and of materials and energy recovered from the waste management system. The waste management system is credited for the materials and energy exported to the surrounding society as we assume that these exports avoid similar production in society. All flows to the environment from the waste management system as well as from upstream and downstream activities are characterized into potential environmental impacts following international standard methods.

It should be emphasized that LCA methods quantify potential environmental impacts of a general nature. This means that the conversion from environmental flows to environmental impacts does not reflect where the emission takes places nor the presence of other sources or of a background level. LCA methods do not address whether a threshold value is exceeded or if further emission can be accommodated before threshold values are exceeded. These aspects are inherent in all LCA models.

The waste considered is the solid waste managed by the authorities and is addressed as “mixed other waste” from households and small commerce and as “food waste” from restaurants, markets and cantinas, as these two waste types are collected separately. Waste treatment facilities may treat both waste types. Most solid recyclables from households and commerce are handled by specific private contractors or in an informal system of collectors and traders driven by economic interests. The recyclables handled by private contractors and the informal sector are not part of the current study. This also means that in our modelling of potential future development of the waste management system in Bengbu we do not consider introducing further source separation and recycling system, except for household food waste.

LCA modelling

The LCA-modelling is done with the EASETECH model using local data to the extent possible and supplemented with external data. The LCA was carried out according to the requirements outlined in the International Standards 14040 and 14044, except that no critical external review has been made. Careful internal review was conducted. The impact categories considered were selected among those recommended by the European Commission: climate change, ozone depletion, human toxicity cancer and non-cancer effects, photochemical ozone formation, ionizing radiation, particulate matter, terrestrial acidification, terrestrial eutrophication, freshwater eutrophication, ecosystem toxicity, resource depletion fossil and abiotic.

In the assessment we emphasize climate change as this is believed to have priority politically. Impacts as photochemical ozone formation, particulate matter, terrestrial acidification, and eutrophication are also consistently assessed, while the toxicity impacts are included in the assessment only when extreme results are observed; this is due to the much higher uncertainty associated with the quantification and characterization of the toxic flows and impacts.

The results are in some cases expressed in "person-equivalents", which represent the amount in each impact category that is associated with all activities (food, housing, transport, travelling etc.) of one average person within one year. The normalization references for the world are used since consistent data relevant for China is not available.

The data used in the LCA-modelling was to the extent possible obtained from the Bengbu authorities. Composition of the MSW was based on local data and assessed against other Chinese data available. The chemical composition of the individual material fractions were obtained from the EASETECH database supplemented with available local data. The data on waste technologies were from local sources, supplemented with data from the EASETECH database and other Chinese studies when necessary to obtain complete and consistent data. External data representing exchanges over upstream and downstream borders were from the EASETECH database or retrieved from the Ecoinvent database (v3.6, consequential).

The modelling and the data used are described in details in the report and the appendix.

Waste

The study deals with Mixed other waste and Food waste. The waste data used are based on actual measurements reported by the City of Bengbu. Occasionally, large variations and some inconsistencies were observed in the data. Future waste characterization should be designed to feed LCA models. In particular, the water content should be in focus as this determines actual mass of solids to be handled.

Mixed other waste: The mixed other waste collected from households was 283 000 tons/year in 2019 and is expected to increase to 347 000 tons/year by 2035. The waste originates from the four districts according to records from 2015-2019.

The water content of the waste is high: 61.5%. On a wet weight basis the waste contains approximately 46.7% food waste, 22.7% plastic,11.4% paper, 5.5% textile, 2.1% wood, 4.3% glass and 0.75% metal. Other fractions amount to 6.5%. The lower heating value is 5.95 MJ/kg wet waste. The ash content is 16.0% on a wet weight basis.

Food waste: Before 2019, the food waste was not separately collected or treated and thus included in the amount of mixed other waste. From 2019, the food waste from restaurant is separately collected but still treated together with mixed other waste; the amount generated in 2019 was 37 900 tons/year. The characteristics of food waste are not measured.

Collection, transfer and transportation

The Mixed other waste is collected from local bins, small compression stations, and 19 transfer stations. The transfer stations apply compression without any sorting of the waste. The Mixed other waste contains the food waste that is not separately collected. The collection of the waste to the transfer stations involves small electrical vehicles (<1.5 t) and small diesel driven vehicles (3 t).The collection uses about 0.84 L diesel and 0.98 kWh electricity per ton of waste in average. The transportation from the transfer stations is by diesel driven trucks with a load of 8~10 t or even 18 t and the diesel use is about 3.3 L diesel/ton of waste. In the modelling the diesel consumption in collection is constant, while the diesel consumption for transport is proportional to distance travelled to the treatment facility.

The food waste from restaurant is separately collected and transferred from the year 2019, but the specific data on food waste collection and transportation are not available.

The diesel consumption is converted to emissions based on assumed exhaust emission standards by matching Chinese standards with European standards as the latter are used in the model.

Treatment

Several treatment and disposal technologies are available or are being built in the Bengbu MSW system:

Anaerobic digestion. The process concept is anaerobic digestion with electricity recovery from the biogas. Large impurities are removed after the food waste enters the treatment plant (technology not specified). Then oil in the waste is separated (technology not specified) and the waste oil is sold to external industry for biodiesel production. The food waste is then routed to anaerobic digestion with a dry process. The generated biogas is sent to combined heat and power generation. The recovered electricity is sold to the grid and the heat used internally to heat the digester. The digestate is planned to produce compost but now is sent to the incinerator located nearby after drying. The biorefinery facility in Bengbu has not been operated formally, and thus no data is available currently. Therefore, we have used the data of biorefinery from Suzhou for the PLANNED time period, and assume performance improvement for the FUTURE.

Incineration: A large incinerator treats 1210 t/d with two grate furnace of 605 t/d. The bunker wastewater is treated in an inner WWTP and then reused. The incineration plant is equipped with a pure condensing steam turbine of 25 MW for electricity recovery. The electricity recovery is 25.2% of the lower heating value: 354-368 kWh/ton of which about 13.3-14.0% is used by the incinerator. No heat is recovered. The flue gas is treated by the air pollution control system and released into the atmosphere. The air pollution control system includes selective non-catalytic NOx-removal, semi-dry and dry acid gas treatment, activated carbon injection and baghouse filter. Diesel and material consumption is accounted for.

Landfilling: In the BASELINE time periods, all of the waste is landfilled. The CURRENT, PLANNED and FUTURE periods do not include landfilling of fresh MSW. The landfill operation includes unloading, spreading, compacting and covering of the waste. The landfill is equipped with bottom liners of HDPE membrane and leachate collection system. HDPE membranes are used for interim cover. Surface water runoff is controlled and kept separate from the leachate. Landfill gas was collected for electricity production from 2014. The leachate was preliminarily treated in a specialized treatment plant using UASB and SBR technology, and the treated water was discharged to sewage network for further treatment in WWTP. The LCA modelling considers emissions for 100 years after the waste is landfilled. During the 100 years period, the fate of the carbon in the generated gas is estimated to: 61.5% as landfill gas collected and used for electricity production, 2.7% flared into to carbon dioxide, 0.0% naturally oxidized, 35.8% escapes to the atmosphere. About 49.0% of the carbon in the waste is not degraded and remains as stored carbon in the landfill.

Energy system

The Chinese energy system is undergoing dramatic changes as China moves towards a greener and more renewable energy system. In the report "China 2050 High Renewable Energy Penetration Scenario and Roadmap" published by Energy

Research Institute of National Development and Reform Commission, a scenario with ideal development of society, policy, economy and technology was introduced to predict the energy structure up to 2050: the total energy consumption will peak around 2025 and renewable energy will increase its contribution significantly. However, by 2050 fossil based energy still constitutes about 25-30% of all primary energy consumed.

The specific development of the Chinese energy system will be decided as part of the 5-year plans and the role of the waste-based energy will be determined as part of the development plans. Thus, currently there is no approach to predict what the waste-based energy will substitute in the future except what can be argued by the Chinese ambition of reducing the contribution of fossil-based energy. Thus we assume in the modelling reaching as far as 2035 that the waste-based energy will substitute for fossil-based energy: Electricity based on coal with a Global Warming Potential (GWP) of 1.0 kg CO_2-eqv./kWh and heating based on natural gas showing a GWP of 12.4 kg CO_2-eqv./1000MJ (0.49 kg CO_2-eqv./m^3). Biodiesel and biomethane are also credited according to their energy content.

Time period overview

The characteristics of the four time period are summarized below

Scenarios	BASELINE	CURRENT	PLANNED	FUTURE
Year	2015-2017	2018-2019	2020-2025	2025-2035
Waste				
Mixed other waste • Amounts	Actual	Actual	Forecasted (3.02×10^5 t/y)	Forecasted (3.47×10^5 t/y)
• Fraction	As observed		Plastic increased, household food waste decreased	
• Food waste separation	No: 0%		Yes: 8% of household food waste	Yes: 20% of household food waste
Food waste • Waste amounts	Actual	Actual	Forecasted (4.06×10^4 t/y)	Forecasted (4.66×10^4 t/y)
• Composition	Constant as in Appendix Table A4			
Technology				
Collection and transport	EURO IV		EURO V	EURO VI
Landfill technology	As in Appendix	Landfill only for inert residues		
Landfill capacity	As reported	No limit for inert residues		
Biorefinery AD	Not established		As in Appendix	Improved performance (biogas generation ratio 80%)
AD capacity	Zero		As reported (100t/d)	No limit
Incinerator	Not in operation	As in Appendix Tables A9-22		Improved performance (electricity recovery ratio 25.8%)
Incinerator capacity	Not in operation	As reported		No limit

Results and conclusion

The overall climate change impact of waste management in Bengbu, Figure S1, was in the BASELINE a load of the order of 19 800 tons of CO_2-equivalents per year primarily due to collection and transport and the use of landfilling. In the CURRENT time period the climate change impact has decreased to 12 700 tons of CO_2-equivalents per year. This decrease is due to the incineration of waste (especially Food waste) with an efficient electricity recovery. In contrast, in the PLANNED time period, anaerobic digestion of Food waste and source-separated food waste is in operation, and the overall impact on climate change further decreases to the order of 11 200 tons of CO_2-equivalents per year. However, the load to climate change from the incineration of Mixed other waste increases, because more plastic waste containing fossil carbon and less food waste with biogenic carbon are incinerated. The FUTURE time period suggests that there is further possibilities for improving the waste management system potentially reaching an overall saving in climate change of about 4 600 tons of CO_2-equivalents per year. This improvement is primarily due to an increase in the amounts of Food waste handled by AD and improvements in source separation of food waste, as well as in biogas yield from anaerobic digestion and energy recovery from incineration. As seen from Figure S1 the climate change impact from collection and transport increases slightly due to the increasing amount of waste suggesting that it may be worth searching for possibilities for reducing the fuel use in collection and transportation. In addition, in all the time periods involving incineration, possibilities for reducing the energy consumption and fossil carbon emissions are also desired, e.g. facilitating plastic recycling, removing non-combustibles prior to incineration, and carbon capture from the flue gas after incineration.

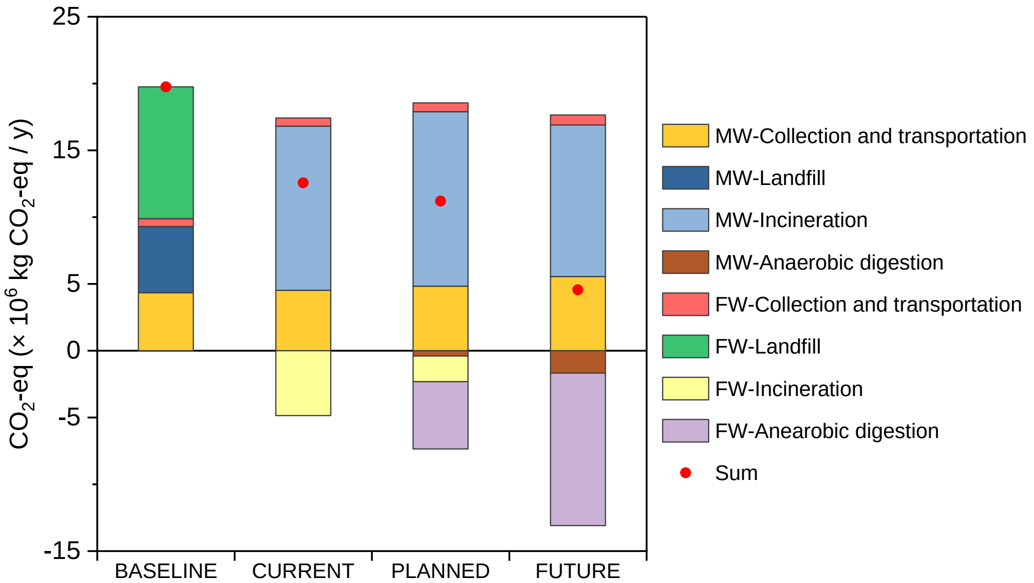


Figure S1: Climate change impacts as CO2-eqv. of total amount of Mixed other waste and Food waste in four periods

(MW: mixed other waste, FW: food waste, AD: anaerobic digestion)

Figure S2 shows the climate change impacts separately for 1000 t of Mixed other waste and for 1000 t of Food waste.

The management of Mixed other waste is a net load to Climate change (34 tons/1000 tons) in the BASELINE time period primarily due to the load from the landfill (Figure S2). Because of the efficient landfill gas collection and carbon storage, the load from the landfill is at a moderate level. In contrast, in the CURRENT and PLANNED time periods where no Mixed other waste goes to landfill, the waste management constitutes a more significant load in Climate change (CURRENT: 60 tons/1000 tons, PLANNED: 58 tons/1000 tons). Incineration of the Mixed other waste constitutes loads in Climate change because significant fossil CO_2 emissions from plastic incineration and relatively low savings from household food waste incineration. With household food waste separation, less waste is incinerated in the FUTURE time period and better performance is expected for incineration and anaerobic digestion, the load to Climate change decreases to 44 tons/1000 tons. The loads from collection and transport are unneglectable.

In the BASELINE time period, the landfilling of Food waste together with the Mixed other waste is a significant load to climate change (287 ton/1000 tons). This is mainly due to the landfill gas emissions from the surface of the landfill or leakage from the landfill gas system. In the CURRENT time period, the Food waste was incinerated together with the Mixed other waste, resulting in a net saving to climate change (-112 ton/1000 tons) because of the recovered electricity substituting for the use of fossil fuels for producing electricity. At the same time, the CO_2 emission from incinerating Food waste is mainly a biogenic carbon emission, which is considered neutral to climate change. In the PLANNED time period, biorefinery of Food waste based on AD is a net saving to climate change though the treated amount is limited by its capacity (-155 ton/1000 tons). This is mainly due to the energy recovery from biogas generated in AD, as well as the incineration of the solid residues separated from AD. In the FUTURE time period where all the food waste is assumed to be managed with AD, the savings to climate change increases to -229 ton/1000 tons.

Transportation of Food waste is also a net load to climate change in all scenarios due to the use of fossil transport fuels and it does not change per 1000 tons of waste over time. In AD, energy recovery from biogas (mainly as electricity and heat for own use) avoids significant impacts to climate change. At the same time incineration of the solid residues from AD also contributes to significant savings due to energy recovery and substitution. Crude oil separated in AD is sold to external process for production of biodiesel, which also contributes to savings on climate change. With the increase in AD capacity in progress, the biogas generation and energy recovery in the AD plant increase synchronously, and thus more benefits will be obtained from biogas utilization.

All other environmental impacts showed low loads and the impacts in the PLANNED time period were all improved compared to the BASELINE time period.

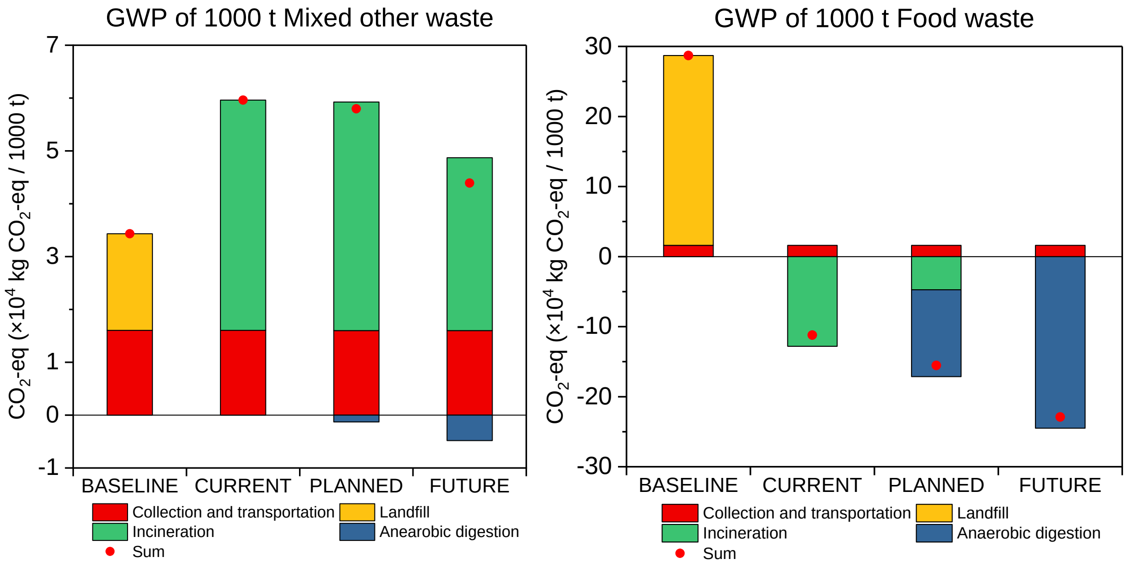


Figure S2: Climate change impacts as kg CO2-eqv. per 1000 tons of wet Mixed other Waste (left) and of Food waste (right) in four time periods

The energy background is extremely important in the climate change impact assessment. In the LCA modelling we have used a fossil-based energy system, which we believe will be the energy technologies affected by the waste system for the years to come. This provides large savings obtained by exporting electricity, gas and fuels to external uses. However, when the background energy becomes greener, the advantages of energy recovery from waste will gradually be reduced and eventually, when electricity is fully renewable, the impact from the waste management system will present a significant net load governed by the fossil content of the waste (Figure S3). If all electricity was supplied by hydro and wind power and all heat (which does not contribute in the Bengbu case) was based on biomass the potential impact on climate change will increase from 4600 tons CO_2-equivalents per year to 148100 tons CO_2-equivalents per year. It is beyond the scope of this study to estimate when the waste management system will exchange with a fully renewable energy system, but it shows that, when considering new investments maybe expected to have a 30-year lifetime, changes in the background energy system must be addressed.

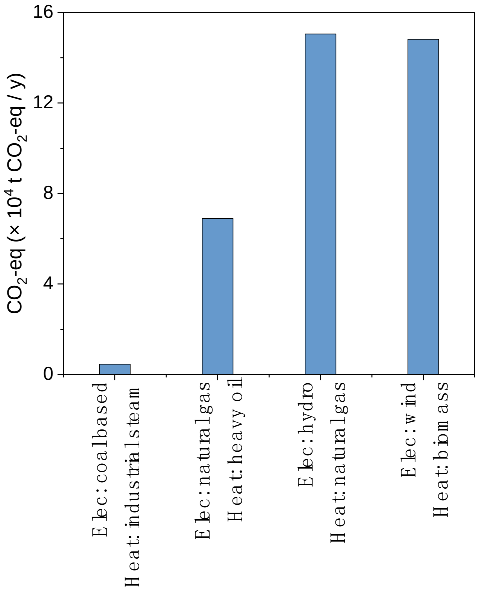


Figure S3: Climate change impacts of the whole waste system in the FUTURE time period with different energy backgrounds.

The sensitivity analyses conducted showed – in addition to the attention to the background energy system - that in terms of optimizing technology parameters focus should be on:

- Increase electricity recovery at incinerator
- Consider heat recovery at the incinerator if an external user can be identified
- Improve source separation of food waste in households
- Decrease electricity use in incinerator
- Decrease electricity use in treatment of bunker leachate
- Reduce fuel consumption in collection and transport of waste
- Increase gas production in anaerobic digestion
- Decrease electricity use in treating wastewater from anaerobic digestion
- Prevent biogas loss in AD plants

In addition, a large mechanical sorting facility is under consideration in Bengbu. LCA results indicate that mechanical sorting of the Mixed other waste can avoid significant climate change impacts by waste recycling and substituting corresponding raw materials including plastics and glass, and at the same time reducing fossil carbon emissions from incineration of plastic. Mechanical sorting also increase food waste separation and increases the savings from biogas utilization in AD. A large mechanical sorting facility is thus considered beneficial from an environmental impact perspective. However, the quality of the sorted materials is crucial for obtaining the estimated credits from substituting the production of virgin materials. We suggest that these aspects be further assessed before any decision is made regarding the establishment of a central sorting facility. In addition, sorting and landfilling of inert factions not suitable for incineration should also be considered, since the incinerator today receives significant amounts of non-combustible waste as part of the Mixed other waste.

We suggest that LCA-modelling becomes integrated into the waste management of Bengbu as part of the reporting of the environmental aspects of the implementation of current plans (by updating the LCA modelling for example every three years to document progress) and as a quantitative tool in assessing new initiative as part of the planning process so new investments can provide significant environmental improvements.

中文摘要

本报告是由北京师范大学（中国北京）和丹麦技术大学（丹麦Kongens Lyngby）以及蚌埠市住房和城乡建设局和GIZ（德国国际合作机构）共同编写，GIZ 北京分部联系电话为：81247064。该报告应引用为：Zhao, Y., Chang, H.M., Damgaard, A., Bisinella, V., Christensen, T.H. (2021): Life cycle assessment of waste management in Bengbu, PR China. GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit), Beijing. 该报告包括60 页的正文和47 页的附件。

引言

近年来，中国固体废物管理体系正在迅速发生变化，垃圾填埋量逐渐减少，而其他处理方式和回收再利用途径逐渐增加。在这一变化中，除了资源、空间和经济因素外，环境影响因素起着十分重要的作用。生命周期评估（LCA）是一个能够量化固废管理过程潜在环境影响的全球公认方法。在过去的二十年中，LCA 已经被很多国家用于评估固废管理的各个方面。LCA 可以量化评估一系列环境影响指标，并明确固废管理系统中产生环境负担和效益的环节。因此，LCA 是一个量化固废管理过程中的环境影响、评估未来的优化潜力的有效工具。

本研究报告通过严格的 LCA 方法评估了蚌埠市生活垃圾管理系统对环境的影响。蚌埠市位于安徽省北部（地理坐标：东经 116°45'-118°04'E；北纬 32°43''-33°30'N）。本研究涵盖了蚌埠市四个行政区产生的生活垃圾，分别为：蚌山区、禹会区、淮上区和龙子湖区，涉及面积 613 平方公里，常住人口 115 万人。

本报告 LCA 研究的时间范围为 2015-2035 年，分为四个时段，分别代表城市固体废物管理的发展情况：“基线”为 2015-2017 年，在中国 IWM NSP 项目开始之前；“现状”为 2018-2019 年，代表当前城市固体废物管理系统，“计划”为 2020-2025 年，代表了中国五年计划中预期的固废管理系统。“未来”是一个假设的城市固体废物管理系统情景，其目的是反映 2025-2035 年期间进一步改善蚌埠市固废系统环境影响的可能。在“未来”时期考虑的潜在改进措施不一定完全符合蚌埠市或德国国际合作机构的观点，引入对这些措施的评估是为了说明如何在规划过程中以定量方式评估废物管理系统的理念与方法，并说明蚌埠市固废系统在环境影响方面有哪些优化潜力。

研究工作中尽最大可能收集并使用了蚌埠市废物管理系统的真实数据，包括已有的固废系统相关规划。因此，所涉及的三个时间段（基线、现状和计划）的 LCA 建模已尽可能接近实际情况，而在“未来”时期，我们在不考虑固废设施实际处理能力限制的情况下，评估了固废系统进一步发展所造成的潜在的环境影响。

LCA 模型量化了固废管理系统中废物、组分和物质流，同时核算了固废管理系统消耗或回收的资源和能源。我们认为回收的资源和能源得以利用，能够避免社会上同类资源或能源的生产，因此固废管理系统能够通过回收相应的资源和能源取得环境效益。按照国际标准方法，固废管理系统及其上游和下游工艺向环境释放的所有物质都会计入其环境影响潜能。

需要强调的是，生命周期评估方法对潜在环境影响进行的是一般性评估。这意味着从环境物质流向环境影响的转换评估，不能反映污染排放所发生的位置，也不能反映已存在的其他污染源或背景水平。LCA 方法不涉及污染排放阈值或标准，从而也不涉及在超过阈值或标准之前的环境容量。上述设定是所有 LCA 研究的通用方法。

本研究中的固体废物是指由市政收集的生活垃圾。由于不同垃圾类型的分类收集，研究中将固体废物分为两类，“其他混合垃圾”指来自居民生活和商业、办公的混合生活垃圾，“餐厨垃圾”主要指来自饭店、农贸市场或食堂的餐厨垃圾。研究所涉及的固废处理设施包括处理这两种垃圾的相应设施。来自家庭和和商业、办公的大多数可回收废物是由私人或经济利益驱动的正式、非正式收集单位收集处理的，因此可回收垃圾不作为本研究的对象。这也意味着在我们对蚌埠市固废管理系统未来发展的建模研究中，除家庭厨余垃圾外未涉及其他源头分类或回收系统。

生命周期评估模型

本研究中利用 EASETECH 模型软件建立相应的 LCA 模型，其中涉及到的数据主要来自于当地实际数据，并适当补充部分外部数据。LCA 的评估工作根据国际标准 ISO 14040 和 ISO 14044 的要求进行，由于条件所限未严格进行外部审查，但进行了严格的内部审查。本报告中涉及的环境影响类别根据欧盟委员会推荐的环境影响类别选择，具体包括：气候变化（温室效应）、臭氧消耗、人体毒性（致癌和非致癌）、光化学烟雾、电离辐射、颗粒物、陆地酸化、陆地富营养化、淡水富营养化、生态毒性、资源消耗（化石类和非生物类）。

考虑到气候变化（温室效应）在国际和中国均十分重视，并符合 GIZ 的项目主旨，因此在本研究与评估中我们重点阐述了固废管理系统对气候变化的影响。本研究还同时评估了对光化学烟雾、颗粒物、陆地酸化和富营养化等环境类别的影响；而由于对毒性相关环境影响的定量与表征不确定性较高，对毒性相关的影响仅在存在突出结果时才纳入评估。

在某些情况下，结果以“人均当量”表示，代表相应类别的环境影响与一个普通人在一年内的所有活动（食品、住房、交通、旅行等）平均影响的相对数量。在计算环境影响的人均当量时，因为没有与中国相关的归一化参数，所以我们使用了世界平均的归一化参数。

LCA 模型中使用的数据主要来自苏州市。城市生活垃圾的组成基于当地实际监测数据，并根据其他可用的中国数据进行了对比核验。每项垃圾组分的化学成分主要从 EASETECH 数据库获得，并利用可获得的当地实测数据进行补充。固废处理技术的数据主要来自当地实际运行数据，必要时补充了 EASETECH 数据库和其他中国相关研究的数据，以获得完整而统一的固废系统 LCA 数据。固废系统上游和下游工艺以及系统交换的外部数据，主要来自于 EASETECH 数据库或 Ecoinvent 数据库（v3.6）中最相关的数据。

为确保研究的透明性、可靠性和可重复性，本报告和附录中详细描述了研究过程中所使用的全部建模数据。

固体废物

本研究中的对象固体废物包括其他混合垃圾和餐厨垃圾。研究中所使用的垃圾组分数据基于蚌埠市的实际监测结果，但在实际监测数据中存在个别差异较大或与实际情况不符之处。建议将来对垃圾组分和成分的分析内容符合 LCA 研究的相关要求。其中，含水率对垃圾的实际质量有决定性影响，因此在分析中应特别关注对垃圾含水率的准确测定。

其他混合垃圾: 2019 年来自于居民生活和商业办公等的其他混合垃圾清运与处理量为 28.3 万吨，并预计在 2035 年增长至 34.7 万吨。根据 2015-2019 年的数据记录，上述垃圾主要来自于蚌埠市的四个辖区。其他混合垃圾的含水率较高，达 61.5%。以湿基为基准，其他混合垃圾中含有 46.7%的家庭厨余垃圾，22.7%的塑料垃圾，11.4%的纸类废物，5.5%的织物，2.1%的木竹，4.3%的玻璃废物，0.75%的金属废物和 6.5%的其他灰渣等，低位热值为 5.95 MJ/kg 湿基，基于湿基的灰分含量为 16.0%。

餐厨垃圾：2019 年之前，蚌埠市的餐厨垃圾没有单独收集或处理，而是与其他混合垃圾一并混合收集并处理。2019 年起，开始对来自餐馆的餐厨垃圾进行单独收集，但 2020 年之前仍和其他混合垃圾一同处理。由此监测的 2019 年餐厨垃圾产生量为 3.79 万吨，并未进行餐厨垃圾的组分监测。

收集、运输和转运站

蚌埠市的其他混合垃圾经由垃圾箱、小型压缩站和 19 个转运站收集转运。转运站普遍采用压缩工艺，并未进行垃圾的筛分或分选。其他混合垃圾中包括了未被源头分类的厨余垃圾。从居民区到转运站的收集车辆主要使用了小型电动车（载重 <1.5 吨）和小型柴油车（载重 3 吨）。收集车收集每吨垃圾平均消耗约 0.84 升柴油和 0.98 kWh 电力。从转运站到垃圾处理设施的转运车辆主要为载重 8~10 吨乃至 18 吨的柴油运输车，转运每吨垃圾的柴油消耗量约为 3.3 升。在 LCA 建模研究中，垃圾收集过程的柴油消耗设为定值，而转运过程的柴油消耗与转运站到处理设施的距离成正比。

来自于餐馆的餐厨垃圾从 2019 年开始单独收集和运输，但是暂时缺乏收集和运输的相关数据。

在 LCA 研究中，车辆柴油消耗造成的尾气排放是基于汽车尾气排放标准进行转化与核算的，在模型中使用了中国尾气排放标准所对应的欧洲排放标准。

处理和处置设施

蚌埠城市固体废物管理系统中已有或在建如下几种处理技术：

厌氧消化：该工艺为包括沼气发电的厌氧消化工艺。餐厨垃圾在进入处理厂后，先去除大量杂质，然后将垃圾中的油脂进行分离，出售给外部企业以生产生物柴油。剩余餐厨垃圾残渣进行干式厌氧消化，产生的沼气通过热电联产回收电能并并入电网，热能用于厂区内部加热厌氧消化罐。厌氧消化的沼渣原计划用于堆肥生产肥料，但目前在干燥后送至附近的垃圾焚烧厂进行焚烧。2020 年，蚌埠市的餐厨垃圾厌氧消化厂试运行，在尚未正式运营期间未获得可用数据。因此， 在“计划”时间段中，我们使用了苏州市餐厨厌氧消化厂的相关数据，并假设在“未来”阶段其性能得以进一步优化提高。

垃圾焚烧： 垃圾焚烧厂的处理能力为 1210 吨/日，由两个焚烧能力为 605 吨/日的炉排炉组成。垃圾贮存坑的渗滤液在内部污水处理厂处理，然后再利用。焚化厂配备有 25 MW 的纯冷凝式蒸汽轮机，用于电力回收。电能回收效率为低位热值的 25.2%，约为 354-368 kWh/t 湿基，其中 13.3–14.0%由焚烧厂自用，没有热能回收。焚烧烟气经烟气处理系统处理后释放到大气中，烟气处理系统工艺主要包括选择性非催化脱氮、半干式和干式脱酸、活性炭吸附和布袋除尘器等。焚烧厂所投入使用的柴油和各类物质、原料消耗均计算在内。

垃圾填埋：在“基准”时间段中，蚌埠市所有垃圾均被填埋。在“现状”、“计划”和“未来”时间段中垃圾全量焚烧，从而不再包括原生垃圾的直接填埋处置。垃圾填埋场的作业主要包括卸载、分铺、压实和覆膜等。该垃圾填埋场设有 HDPE 膜的防渗衬层和渗滤液收集系统。HDPE 膜也用于临时覆盖，以控制地表水径流实现雨污分流。该填埋场从 2014 年开始收集填埋气并用于发电。渗滤液在专门的渗滤液处理厂中采用 UASB 和 SBR 技术进行初步处理，处理后的水排入污水管网，之后进入污水处理厂进一步处理。LCA 模型考虑了垃圾填埋后 100 年内的排放情况。在 100 年的时间里，所产生的填埋气中碳的流向估算为：61.5%作为填埋气收集并用于产电，2.7%被火炬点燃以二氧化碳释放，0.0%为自然氧化，35.8%释放到大气中。填埋垃圾中 49%的碳在 100 年内仍不会被降解，而是作为贮存碳被保留在堆体中。

能源系统

随着中国向更绿色、更可再生的能源体系发展，中国的能源体系正在发生巨大变化。国家发展和改革委员会能源研究所发布的《中国 2050 年高可再生能源普及率情景和路线图》报告中，介绍了一种社会、政策、经济和技术发展的理想情景，以预测到 2050 年的能源结构，预估总能源消耗将在 2025 年左右达到峰值，而可再生能源的占比将大大增加。但到 2050 年，基于化石的能源仍将占所有一次能源消耗的 25-30%。

中国能源系统的具体发展将作为五年计划的重要组成，而固废能源也将作为发展计划的一部分。除了中国减少化石能源使用比例的努力目标，目前尚难以准确预测未来由废物回收的能源将替代除化石能源外的其他能源类型。因此，在到 2035 年的所有时间段模型中，我们假设基于废物回收的能源均替代基于化石的能源，包括基于化石的电能所产生的气候变化潜能为 1.0 kg CO_2-eqv./kWh 和基于天然气的热能产生的气候变化潜能为 12.4 kg CO_2-eqv /1000 MJ（0.49 kg CO_2-eqv./m^3）。生物柴油和生物甲烷也根据其能量在需要时纳入计算。

时间段（情景）概述

研究中涉及的四个时间段（情景）的特征如下表所示。

时间段（情景）	基线	现状	计划	未来
年份	2015-2017	2018-2019	2020-2025	2025-2035
废物				
其他混合垃圾 • 产生量 • 成分 • 厨余垃圾分类	真实值	真实值	预测值 (3.02×10^5 t/y)	预测值 (3.47×10^5 t/y)
	根据实测数据		塑料增加，家庭厨余垃圾减少	
	无：0%		分出率：8% 家庭厨余垃圾	分出率：20% 家庭厨余垃圾
餐厨垃圾 • 产生量 • 组分	真实数据	真实数据	预测值 (4.06×10^4 t/y)	预测值 (4.66×10^4 t/y)
	详情见附录 表 A4			
技术				
收集和转运	欧 IV 标准排放		欧 V 标准排放	欧 VI 标准排放
填埋技术	详情见附录	只填埋惰性残渣		
填埋能力	详情见报告正文	对惰性残渣填埋无限制		
厌氧消化技术	未建		详情见附录	性能提升（沼气产率 80%）
厌氧消化能力	未建		详情见报告正文（100t/d）	无限制
焚烧技术	未运行	详情见附录 表 A9-22		性能提升（电能回收率 25.8%）
焚烧能力	未运行	详情见报告正文		无限制

结果和结论

图 S1 显示了蚌埠市固体废物管理系统对气候变化（温室效应）的总体影响，在“基线”中，每年的影响负荷约为 1.98 万吨二氧化碳当量，这主要来自于收集、运输和垃圾填埋环节。在“现状”时间段内，气候变化影响已降至每年 1.27 万吨二氧化碳当量，这主要是因为固体废物（尤其是餐厨和厨余垃圾）由填埋转为焚烧，进行了高效的电能回收。进而，在“计划”时间段中，对餐厨垃圾和分类回收的厨余垃圾进行厌氧消化，可使对气候变化的总影响进一步降低至每年约 1.12 万吨二氧化碳当量。然而，焚烧其他混合垃圾对气候变化造成的负担有所增加，这是因为含化石碳的塑料垃圾焚烧量增加，而含生物碳的厨余垃圾焚烧量减少。在“未来”时间段中，通过进一步完善固体废物管理系统，每年对气候变化的影响可降低至 0.46 万吨二氧化碳当量。这一减排效果主要是由于餐厨垃圾以及实行垃圾分类而分出的家庭厨余垃圾的量有所增加，进而增加了厌氧消化处理量以及沼气产量，沼气燃烧的能量回收也随技术优化而改善。从图 S1 可以看出，由于垃圾处理量的增加，收集和运输环节对气候变化的影响略有增加，这说明采用更加环保的收集和运输方式是值得考虑的。另外，在包括焚烧技术的所有时间段中，焚烧能耗和化石碳排放的降低仍有优化空间，例如，促进塑料的回收利用、在焚烧前筛分去除不可燃组分，以及从焚烧烟气中进行碳捕集。

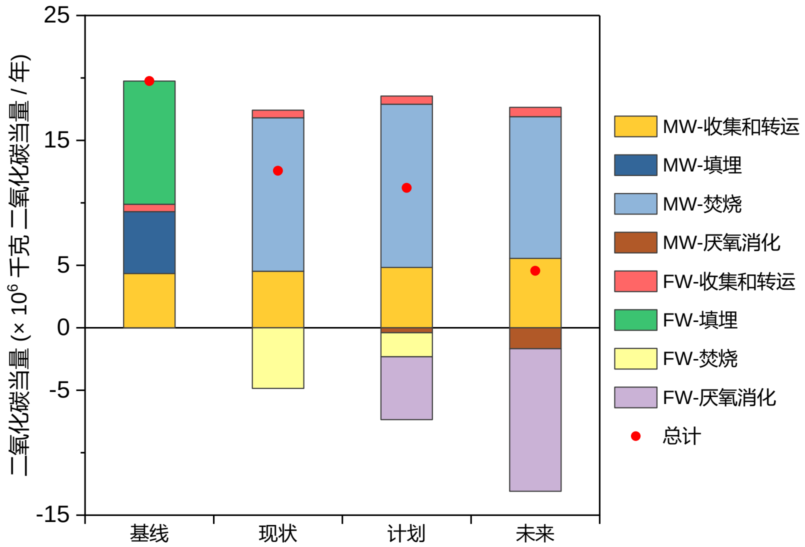


图 S1：四个时期中其他混合垃圾（MW）和餐厨垃圾（FW）处理过程对气候变化的影响（以二氧化碳当量表示）

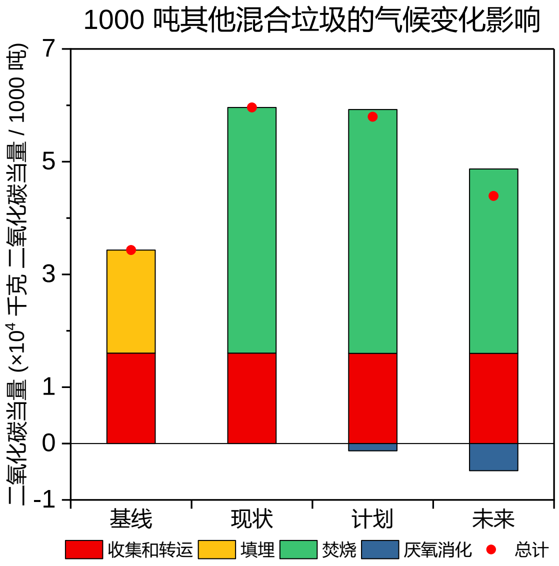
图 S2 分别展示了 1000 吨其他混合垃圾和 1000 吨餐厨垃圾处理对气候变化的影响。

其他混合垃圾的处理在“基线”期间造成了一定的气候变化影响（34 吨二氧化碳当量/1000 吨），这主要是由于垃圾填埋场产生的甲烷等碳排放（图 S2），但由于有效的填埋气收集和碳贮存，垃圾填埋场的碳排放仅处于中等水平。然而，在“现状”和“计划”的时间段内，其他混合垃圾未进入垃圾填埋场，而是采取焚烧处理，处理系统对气候变化造成了更大的影响负担（现状：60 吨二氧化碳当量/1000 吨，计划：58 吨二氧化碳当量/1000 吨）。其他混合垃圾的焚烧造成了更大的碳排放，主要是由于塑料废物的焚烧排放了大量的化石二氧化碳，而厨余垃圾的焚烧可以通过发电替代化石能源相对减少化石碳的排放。随着家庭厨余垃圾分类，在“未来”时间段内焚烧的垃圾量有所减少，焚烧和厌氧消化的性能有望得到提高，从而将对气候变化的影响减少到 44 吨二氧化碳当量/1000 吨。此外，来自收集和转运造成的碳排放也是不可忽略的。

在“基线”时间段内，厨余垃圾的填埋造成气候变化负担的重要原因（287 吨二氧化碳当量/1000 吨）。这主要是由于填埋场表面的填埋气释放或填埋气收集系统泄漏造成的碳排放。在“现状”时间段内，餐厨垃圾与其他混合垃圾一起焚烧，由于回收的电能能够替代化石燃料发电，从而可以避免对气候变化造成相应影响（-112 吨二氧化碳当量/1000 吨）；同时，由于厨余垃圾焚烧产生的二氧化碳排放主要是生物碳排放，研究公认其对气候变化没有影响。在“计划”的时间段内，尽管餐厨垃圾的厌氧消化处理量受到处理能力的限制，但仍可以显著减少碳排放（-155 吨二氧化碳当量/1000 吨），这主要是由于厌氧消化过程中沼气的能量回收和沼渣焚烧的能量回收。在“未来”时间段内，所有的餐厨垃圾都采用厌氧消化技术处理，相应的碳减排可以提高到-229 吨二氧化碳当量/1000 吨。

在所有时间段下，由于使用化石燃料驱动收集运输车辆，餐厨垃圾的运输也对气候变化产生了不利影响，并且不随时间发生变化。在厌氧消化技术中，从沼气中回收能量（主要是电和自用热）可以避免较大的气候变化影响。同时，沼渣进行焚烧并回收剩余能源，以及分离出的粗油出售用于生产生物柴油，均可以有效减少温室气体的排放。随着厌氧消化处理能力的提高，厌氧消化厂中沼气产量和能量回收同步增加，使得沼气利用将获得更大的环境效益。

所有其他环境影响类别均仅有较低的影响负荷，并且与“基准”时间段相比，“计划”时间段内的对各类别的环境影响均得到了一定程度的改善。



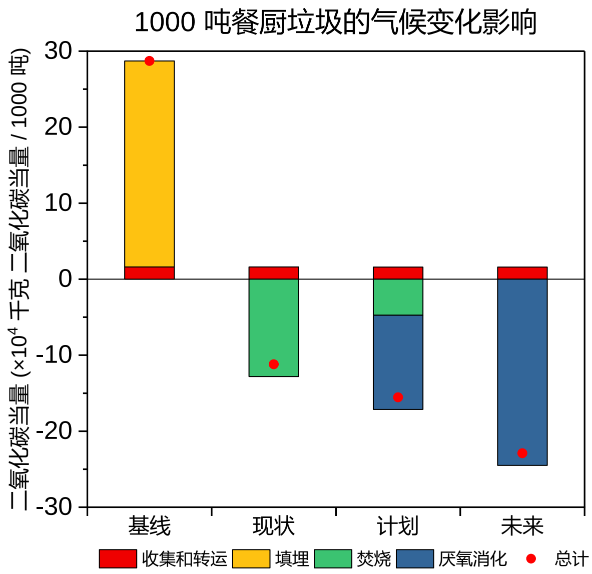


图 S2：四个时间段中每 1000 吨其他混合湿垃圾（左）和餐厨垃圾（右）
处理对气候变化的影响（以二氧化碳当量表示）

固废系统所处的能源背景在气候变化影响评估中极为重要。在 LCA 研究中，我们使用了基于化石能源的背景能源系统，这也是当前和短期内与固废系统有直接关系的的能源背景。通过将固废处理系统中回收的电能、天然气和其他燃料输出到系统之外并利用，可以节省大量原生资源或能源。但是，当背景能源变得更加绿色时，从废物中回收能源的优势将逐渐减小。而当背景能源系统中的电能完全来自于可再生能源时，固废处理系统将表现出更大的环境影响符合，这主要来自于废物中存在的化石碳释放（图 S3）。如果所有电能均由水力或风能提供，并且所有热能都来自于生物质能源（热能在蚌埠案例中没有贡献），那么固废系统对气候变化的潜在影响将从每年排放 0.46 万吨二氧化碳当量增加到 14.81 万吨二氧化碳当量。固废系统在什么时间内将完全实现与可再生能源系统进行交互，不在本研究的范围之内，但是现有结果表明，在考虑投资建设新设施或新技术、并预期服务于未来 30 年时，必须考虑背景能源系统的变化所带来的环境影响变化。

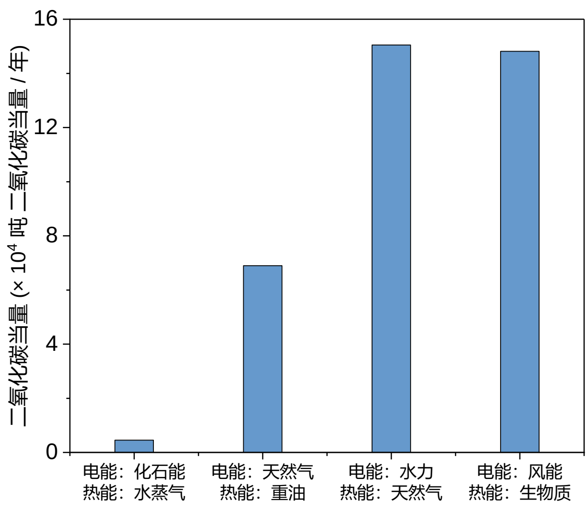


图 S3：“未来”时间段不同能源背景下整个固废系统对气候变化的影响

敏感性分析表明，除了对背景能源的关注外，在优化技术参数方面应重点关注以下方面：

- 提高焚烧厂的电能回收效率
- 如果能够确定热能的外部使用形式，应考虑焚烧厂的热量回收利用
- 提高居民家庭厨余垃圾的源头分类比例
- 减少焚烧厂的电能消耗
- 减少垃圾渗滤液处理环节的电能消耗
- 减少垃圾收集和转运过程中的化石能源消耗
- 提高厌氧消化环节的沼气产率
- 降低厌氧消化后废液处理的电能消耗
- 避免厌氧消化罐沼气的泄露

此外，蚌埠市正在考虑建设大型机械分选设施。LCA 结果表明，对其他混合垃圾进行机械分选可以提高废物循环利用率，并替代相应原材料的使用（包括塑料和玻璃等），从而减少塑料焚烧产生的化石碳排放，进而减轻对气候变化的不利影响。机械分选还可以一定程度增加厨余垃圾的分出率，从而提高厌氧消化中沼气产量和利用。因此，从环境角度而言，大型机械分选设施对综合环境影响和碳减排是有改善作用的。然而，分选物料的品质对其替代原生材料的使用并取得环境效益是至关重要的。我们建议在建设集中分选设施前，进一步评估分选效果和预期品质等方面。此外，当前焚烧工艺中处理了其他混合垃圾中的大量不可燃组分，在建设分选设施时还应考虑对不适合焚烧的惰性材料进行筛分和填埋。

我们建议将 LCA 模型研究整合到蚌埠市的固体废物管理体系中，可以作为规划实施在环境保护或碳减排方面成果报告的部分内容（如每三年更新一次 LCA 模型研究以记录固废系统发展情况），并将其作为定量分析工具，在规划过程中评估新投资或建设方案，以确定新方案对改善环境有显著效益。

1 Introduction

Solid waste management is changing rapidly these years in China, moving away from landfills and increasing treatment and recycling of waste. Environmental considerations play a significant role in this change, but also aspects about resources, space and economy are important.

Life cycle assessment (LCA) is able to quantify the potential environmental impacts of waste management and has been used in addressing many aspects and in many countries during the last two decades. LCA quantifies a range of impacts and identifies where environmental loads and savings take place within the waste management system. Thus, LCA is a helpful tool in quantifying environmental progress within waste management and in assessing potential further improvements to be considered in the future.

This report quantifies by stringent methods the environmental impacts of waste management in the City of Bengbu, PR China covering the period 2015-2035.The time horizon is divided into four time periods representing the actual development in the waste management for the city: 2015-2017 representing the "baseline" (prior to the start of the China IWM NSP), 2018-2019 representing the "current MSW system", 2020-2025 representing the "planned MSW system" as expected within the 5-year plan, and 2025-2035 representing the "future MSW system".

Data on the Bengbu waste management system has been collected on location to the extent possible. Existing plans have been included. The three first time periods considered – BASELINE, CURRENT and PLANNED – thus have been modelled as closely to the actual situation as possible, while in the FUTURE time period we have quantified the environmental impacts of further developments that potentially could be considered. These potential improvements do not necessarily reflect the views of Bengbu City nor GIZ: they have been introduced to illustrate how ideas about waste management can be assessed in a quantitative way as part of a planning process and to illustrate how much room for improvement could be available from an environmental point of view.

The LCA-modelling quantifies the flows of waste, materials and substances through the waste management system, while simultaneously keeping an account of exchanges of materials and energy needed to operate the waste management system and of materials and energy recovered from the waste management system. The waste management system is credited for the materials and energy exported to the surrounding society as we assume that these exports avoid similar production in society. All flows to the environment from the waste management system as well as from upstream and downstream activities are characterized into potential environmental impacts following international standard methods.

It should be emphasized that LCA methods quantify potential environmental impacts of a general nature. This means that the conversion from environmental flows to environmental impacts does not reflect where the emission takes places nor the presence of other sources or of a background level. LCA methods do not address whether a threshold value is exceeded or if further emission can be accommodated before threshold values are exceeded. These aspects are inherent to all LCA models.

The waste considered is the solid waste managed by the authorities and is addressed as "Mixed other waste" form households and small commerce and as "Food waste" from restaurants, markets and cantinas, as these two waste types are collected separately. Waste treatment facilities may treat both waste types. Most solid recyclables from households and commerce are handled by specific private contractors or in an informal system of collectors and traders driven by economic interests. The recyclables handled by private contractors and the informal sector are not part of the current study. This also means that in our modelling of potential future development of the waste management system in Bengbu we do not consider introducing further source separation and recycling system, except for household food waste.

The report contains after this short introduction (chapter 1), a chapter describing the specific LCA-modelling approach for Bengbu (chapter 2), followed by a chapter summarizing the data that has been collected about the Bengbu waste management system (chapter 3). The main features of modelling of the Bengbu waste management system for the four time periods are summarized (chapter 4) and the results are summarized in a following chapter (chapter 5). Details can be found in the Appendix. Finally, conclusions are presented (chapter 6).

2 LCA Methodology

This section describes the goal and scope of the LCA conducted: The specific goals, the scope (functional unit, geographical scope, time horizons, system boundaries, technological scope, modelling approach), and the LCA modelling method (tool, impact assessment, data).

The final receiver of the study is GIZ, Deutsche Gesellschaft für Internationale Zusammenarbeit, who has financed the study. The experiences from the project and the results of the work as presented in this report will support GIZ in determining how they address environmental aspects of waste management in their future work with Chinese cities and Chinese national government bodies.

The specific results for Bengbu may also be used by the local government in managing and improving its own waste management system.

It is also part of the aim to make technical data about Chinese waste management technologies available for future waste LCA studies in China.

2.1 LCA goal

The goal of this study was to quantify for Bengbu the potential life cycle environmental impacts of their current waste management system and of potential future developments of the system. The aim of the study was to:

- Map the flows of waste, material fractions and key elements in the waste
- Quantify potential environmental impacts of how waste management in Bengbu has developed in the period 2015-2020
- Identify where crucial information is lacking
- Learn where environmental loads and savings are obtained
- Quantify potential environmental impacts of the planned waste management systems (2020-2025) in order to show how LCA can be used to identify the environmental aspects as part of a planning process
- Identify the technological and management issues within a future waste management system that are crucial for good environmental performance

2.2 Scope

The scope defines the technical framing of the conducted LCA.

Functional unit

The role of the functional unit definition in LCA is to ensure that the environmental assessment of the systems is based on a fair basis for comparison, in this case the fulfilment of the same functionality.

The functional unit is: Managing the municipal solid waste in Bengbu from the point where the waste is generated over collection, treatment, recycling and final disposal with a view to potential improvements in the waste management system.

The reference flow is 1000 ton (1000 t) of wet waste for each of the two types as they appear in the city; this implies that two waste flows differ in composition. The total impact of the waste management in Bengbu is estimated by multiplying with the actual amounts of each waste type within the specific period.

Geographical scope

The geographical scope is Bengbu City, Anhui province including its immediate surroundings as defined by the current waste management administration. The waste composition as well as the current waste management system may differ significantly between Chinese cities and learnings and conclusions should only be extrapolated to other cities with great care. The waste management system may interact significantly with the energy system and differences in regional energy system may thus affect the result and limit the generality of the results as well.

Time horizons

The time horizon for the waste management systems considered are 2015 to 2035. This time horizon is partly defined by the overall time frame considered in in the China Integrated Waste Management NAMA Support Project (China IWM NSP). The time horizon has 4 periods: 2015-2017 representing the BASELINE (prior to the start of the China IWM NSP), 2018-2019 representing the CURRENT MSW system, 2020-2025 representing the PLANNED MSW system as expected within the 5-year plan, and 2025-2035 representing the FUTURE MSW system. The modelling addresses the four time periods separately and does not provide detailed modelling of the transitions between the time periods.

The time horizon for environmental emissions considered is set at 100 years. This is relevant for emissions linked to landfills and to use of organic residues on land. In particular, emissions related to leaching from landfills may persist longer than 100 years. The 100-year period is often used in waste LCA modelling as it is considered a reasonable compromise between the data series available from relevant technologies and our trust in extrapolating these data.

The time horizon of the environmental impacts is 100 years. This is a common choice in waste LCA, but crucial regarding the climate change impacts, since a long time horizon averages the impact and yields lower characterization factors, meaning that an emission of a greenhouse gas is a smaller load to the climate change when a long time period is considered.

2.3 System boundaries

The waste management system is defined from the point where the waste is generated until its final routing into recycling or utilization. The waste is considered without any upstream burden (zero boundary), which means that waste prevention as such cannot be included in the current study.

The upstream system boundaries include all materials and energy imported into the system to fulfil its functionality: goods, materials and energy. However, any capital goods in terms of construction of buildings, vehicles, equipment and infrastructure are excluded.

The downstream boundary includes exchanges with the surrounding society in terms of materials for recycling, organic waste used on land and energy exported to the public grid or external users.

2.4 Technological scope

All available and relevant data on the specific waste management systems in Bengbu has been collected and fitted to currently existing generic technologies within an existing model (see later); focus is on critical parameters of importance for the environmental assessment. Resources for extensive monitoring of specific technologies within the waste management system of Bengbu have not been available in the current project. The modelling pays attention to actual capacities of existing facilities, but does not necessarily address individual plants.

Waste management technologies considered in the future scenarios are limited to technologies available in the EASETECH database and new documented technologies with sufficient data that can easily form the basis for creating a new technology in the EASETECH database.

The exchange with the energy system is of great importance in assessing most waste management systems. Data on the energy systems have been obtained as regional data from the Ecoinvent database. The potential development in the Chinese energy systems has been approached in the scenario sensitivity analysis by a range of simulations with greener single technologies of relevance for the future.

2.5 Modelling approach

The modelling approach used was consequential LCA since focus is on how the current waste management systems can be improved in the years to come. A consequential approach has also been used for the BASELINE and CURRENT waste management system in order to allow for comparison with potential future improvements.

Multi-functionality in the model was addressed by crediting the system for avoided burdens outside the system. This means, for example, that electricity produced from the waste and delivered to the public grid creates a credit to the waste management system equal to the burden that it would have been in the energy system to produce the same amount of electricity.

The consequential approach implies that the exchanges over the boundaries relate to marginal technologies, meaning technologies that are affected by the deliveries to or from the system. This issue is particularly crucial if the exchange from the waste system is significant relative to size of the market. We have used marginal technologies where possible, otherwise average technology data have been applied.

LCA Modelling

The LCA carried out in this project was conducted according to the requirements outlined in the International Standards 14040 and 14044 (ISO, 2006a, 2006b), except that no critical external review has been made. Internal review of the work has been conducted.

Modelling tool

The study was carried out with the waste-LCA model EASETECH (Clavreul et al., 2014), which was developed at DTU Environment. EASETECH allows modelling of the flow of material in the LCA as a mix of material fractions (e.g. plastic, paper, etc.) and tracking their physico-chemical properties (e.g. energy content, fossil carbon, etc.) throughout the modelled life-cycle steps. The tracking of the material composition on top of the conventional mass flow-based LCA allows consumption and production of resources to be based on the physico-chemical properties of the reference flow, and especially to express emissions occurring during the end-of-life phases as a function of the chemical composition of the waste (e.g. fossil carbon emitted during incineration).

The EASETECH model has been used and documented in a range of waste studies around the world. More than 50 scientific journal contributions have been published using the model.

2.6 Impact assessment (LCIA)

The impact categories for the impact assessment were selected among those recommended by the European Commission (European Commission, 2010). The selected impact categories mid-point impacts were: climate change, ozone depletion, human toxicity cancer and non-cancer effects, photochemical ozone formation, ionizing radiation, particulate matter, terrestrial acidification, terrestrial eutrophication, freshwater eutrophication, ecosystem toxicity, resource depletion fossil and abiotic.

In the assessment we emphasize climate change as this is believed to have priority politically. Impacts as photochemical ozone formation, particulate matter, terrestrial acidification, and eutrophication are also consistently assessed, while the toxicity impacts are included in the assessment only when extreme results are observed; this is due to the much higher uncertainty associated with the quantification and characterization of the toxic flows and impacts.

Results are presented as characterized impacts following the characterization references in Table 2.1. The LCIA results presented in this LCA study are generic potentials and do not predict impacts on category endpoints, threshold levels, safety margins or risk levels, nor impacts associated with the specific city and surroundings.

The results are also expressed in "person-equivalents", where one person-equivalent represents the amount in each impact category that is associated with all activities (food, housing, transport, travelling etc.) of one average person within one year. The normalization references for the World (Table 2.2) are used since consistent data relevant for China is not available.

Table 2.1: Impact category, characterization model, indicator and classification level (level I is best) as recommended by ILCD (EC-JRC, 2011)

Impact category	Characterization model	Indicator	Classification
Climate change	Baseline model of 100 years of the IPCC (Forster et al., 2007). Modelled as in Recipe 2008.	Radiative forcing as global warming potential (GWP100)	I
Stratospheric ozone depletion	Steady-state ODPs from the WMO assessment (latest WMO published ODP equivalents) (Montzka and Fraser, 1999) and the ReCiPe2008 data sets (v1.05).	Ozone depletion potential (ODP)	I
Human toxicity, cancer effects	USEtox model v.1.01 (Rosenbaum et al., 2008)	Comparative toxic unit for humans (CTUh)	II/III
Human toxicity, non-cancer effects	USEtox model v.1.01 (Rosenbaum et al., 2008)	Comparative toxic unit for humans (CTUh)	II/III
Particulate matter/respiratory inorganics	Compilation in Humbert, 2009 based on Rabl and Spadaro, 2004 and Greco et al., 2007	Intake fraction for fine particles (kg PM2.5-eq/kg) – PM2.5eq	I/II
Ionizing radiation, human health	Human health effect model as developed by Dreicer et al. (1995) (ref. Frischknecht et al. 2000) Modelled as in Recipe 2008.	Human exposure efficiency relative to U235	II
Photochemical ozone formation	LOTOS-EUROS (van Zelm et al., 2008) as applied in ReCiPe 2008 v 1.05	Tropospheric ozone concentration increase	II
Acidification	Accumulated exceedance (Posch et al., 2008; Seppälä et al., 2006)	Accumulated exceedance (AE)	II
Eutrophication, terrestrial	Accumulated exceedance (Posch et al., 2008; Seppälä et al., 2006)	Accumulated exceedance (AE)	II
Eutrophication, freshwater	EUTREND model as implemented in ReCiPe.	Residence time of P in freshwater end compartment	II

Eutrophication, marine	EUTREND model as implemented in ReCiPe	Residence time of N in marine end compartment	II
Ecotoxicity, freshwater	USEtox model v.1.01 (Rosenbaum et al., 2008)	Comparative toxic unit for ecosystems (CTUe)	II/III
Resource depletion, mineral and fossil	CML 2002 (Guinée et al., 2002)	Scarcity	II

Table 2.2: Normalization factors (ILCD recommended EC-JRC)

ILCD Impact Category	Unit	EC-JRC Global (2010 or 2013), per person (Benini et al., 2015)
Climate change	kg CO2 eq. /PE/year	7.07×10^{3}
Ozone depletion	kg CFC-11 eq. /PE/year	1.22×10^{-2}
Human toxicity, cancer effects	CTUh/PE/year	1.24×10^{-5}
Human toxicity, non-cancer effects	CTUh/PE/year	1.55×10^{-4}
Particulate matter/Respiratory inorganics	kg PM2.5 eq. /PE/year	5.07
Ionizing radiation, human health	kBq U235 eq. (to air) /PE/year	2.41×10^{2}
Photochemical ozone formation, human health	kg NMVOC eq. /PE/year	4.53×10
Acidification	mol H+ eq. /PE/year	5.61×10
Eutrophication terrestrial	mol N eq. /PE/year	1.64×10^{2}
Eutrophication freshwater	kg P eq. /PE/year	6.54
Eutrophication marine	kg N eq.	3.04×10
Ecotoxicity freshwater	CTUe	3.74×10^{3}
Resource depletion, mineral, fossils and renewables	kg Sb eq.	1.93×10^{-1}

2.7 Data

Data on types of waste included in municipal solid waste (MSW) and the corresponding amounts were obtained from the Bengbu authorities. Composition of the MSW was based on local data and assessed against other Chinese data available. The chemical composition of the individual material fractions were obtained from the EASETECH database supplemented with available local data.

The data on waste technologies were from local sources, supplemented with data from the EASETECH database and other Chinese studies when necessary to obtain complete and consistent data.

External data representing exchanges over upstream and downstream borders were from the EASETECH database or retrieved from the Ecoinvent database (v3.6, consequential). Where exceptions were made of necessity, the text reflects so.

The technologies included in the future scenarios were chosen in collaboration with GIZ and the Bengbu authorities in order to parallel technologies that potentially could be considered in the future, but they do not represent any official plans.

All LCA modelling involves cut-offs, which means minor flows within the system or over the boundaries that are not quantified and thus not contribute to the overall results. The cut-offs should constitute less than 5% of the overall results, but in practice many cut-offs made are based on tradition and experience from other similar projects and thus not always documented.

Regarding the datasets retrieved from the Ecoinvent database, the consequential version of the database is considered consistent with the goal and scope of this LCA study. The version of the database employed for this LCA was the latest available (3.6). All datasets used for this study have been tested for their environmental impacts against other datasets for similar materials and energy before being selected and implemented in the modelling.

The quality and representativeness of the data used in the project are addressed in the report and the interpretation of the results and the conclusion made in the project are done with a critical view to the data available for the LCA modelling.

3 Data on Waste Management in Bengbu

This section describes the current waste management system in Bengbu and presents the available data. The description includes types of waste handled, annual amounts, collection systems in place, information available about waste composition (fractions, content), information about current facilities (location, capacity, technology, availability of technical data, etc.) and eventual plans for changes and investment within the next 5 years. A map showing the major treatment and disposal facilities is also included.

The information described in this section originate from field investigations, regular technical report, monitoring statistics, and previous investigations under the NAMA project in collaboration with local authorities and GIZ.

Data are reported from 2015 and forth where available. Where no data were available the tables show "ND" (No Data). The system and data used in the modelling are described in chapter 4 and in details in Appendix.

3.1 Bengbu

Bengbu is located in the north of Anhui Province, with the latitude of 32°43' to 33°30' N and longitude of 116°45' to 118°04'E. Bengbu is located at the border of the subtropical monsoon climate zone and the temperate monsoon climate zone, with an average temperature of 15.5 °C and an average annual precipitation of 933 mm.

According to the key implementation scope of the National Appropriate Mitigation Actions (NAMA) project in Bengbu, the studied waste system in Bengbu refers to that dealing with the waste generated in the four urban districts (i.e. Bengshan District, Yuhui District, Huai Shang District, and Longzihu District) covering 614 square kilometres and 1.15 million people in total. The management department of environmental sanitation of the Bengbu City Administration and Law Enforcement Bureau is responsible for the management of the city's appearance and environmental sanitation including the task of municipal solid waste (MSW) management. A map showing the districts and major treatment and disposal facilities is shown in Figure 3.1.

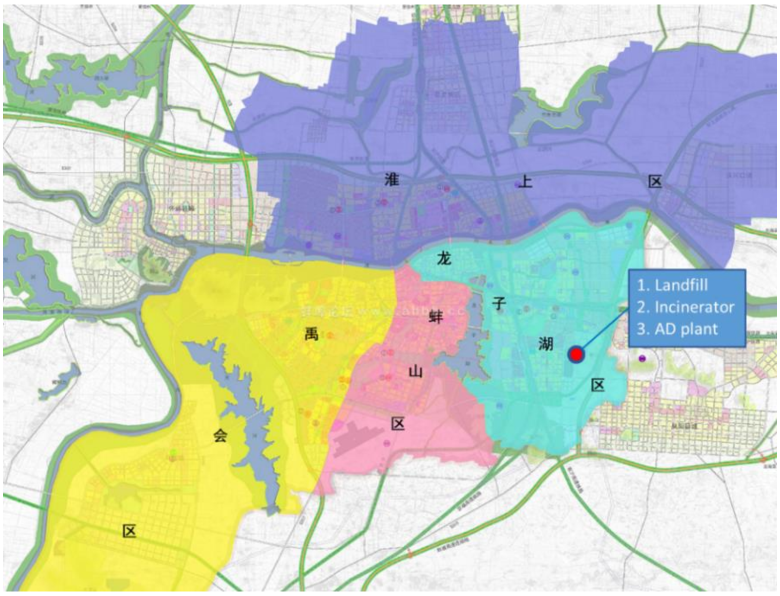


Figure 3.1: Map showing the four districts and major treatment and disposal facilities in Bengbu

The population within the relevant 4 districts was rather stable (~1%) from 2015 to 2018 as shown in Table 3.1.

Table 3.1: Development in population within the five Bengbu districts from 2015 to 2018 (official statistics).

District	2015	2016	2017	2018
Longzihu District	183694	181828	176850	174904
Bengshan District	328198	335473	337260	342970
Yuhui District	356238	359385	359795	360267
Huai Shang District	268054	272557	274934	278560
Total	1136184	1149243	1148839	1156701

3.2 Bengbu's waste management system

In 2018, the Office of the People's Government of Bengbu issued the Work Plan for MSW Classification in Bengbu City, which clearly requires the public institutions to carry out the compulsory classification of MSW. By the end of 2020, all relevant enterprises in the city shall conduct compulsory classification with full coverage of the city and 50% coverage of the suburbs. All residential communities in the urban area shall fully conduct guided classification. Currently, Bengbu adopts the three-category method of MSW classification, separating MSW into recyclable, non-recyclable, and hazardous waste. It is expected that the four-category method will be adopted in order to realize separate collection and transportation of household food waste, when the treatment facility for restaurant food waste has been completed. Details about the general information on the waste system of Bengbu is available in "Baseline Study Report on Waste Management of Demonstration Municipalities" shared within the NAMA project by GIZ.

The MSW system of Bengbu consists of four levels of (technical) units, including generation, collection and transportation, treatment and disposal, and recovery and residue treatment, as shown in Figure 3.2. The system is briefly described according to MSW categories separated at source:

- Recyclables: The amount of recyclables generated was 7030 t/y in 2017 and 16634 t/y in 2018, including waste paper, plastic bottles, cans and scrap metal, glass and others. The recyclables are collected, sorted, traded and treated mainly by specific companies.
- Hazardous waste: The amount of hazardous waste generated was 396 t/y in 2018 and a similar amount is estimated for 2019, including waste lamps, used batteries, expired drugs, etc. The hazardous waste is collected and temporarily stored, and then safely treated by licenced facilities outside of Bengbu with the approval by the sanitation department.
- Food waste: The amount of food waste collected from restaurants was 37888 t/y in 2019. Currently the food waste is separately collected and transported, and then treated in the incinerator together with mixed other waste. The food waste is supposed to be treated in a newly-built AD plant. With the promotion of compulsive source separation, the food waste from household is supposed to increase in the near future.
- Mixed other wastes: The total amount of waste generated was reported as 319100 t/y in 2018 and 320500 t/y in 2019 including both Food waste and Mixed other waste. Therefore, the amount of Mixed other waste was calculated as 281 400 t/y in 2018 and 282 600 t/y in 2019. The mixed other waste is collected, transferred and transported by the sanitation department, and finally disposed in the landfill (before 2018) or treated in the incineration facility (after 2018) located at the same place. The waste route was fully shifted from landfill to incineration from 2018 without any interim period.

According to the goal and scope of this study as well as the actual situation in management and regarding data, the boundary of the current studied system includes the flows of Food waste and Mixed other waste, but excludes the flows of Recyclables and Hazardous waste, as shown in Figure 3.2.

The data on Bengbu's waste management system are mainly based on the data collected or updated in 2020 (from waste system managers, facility operators and company directors), unless otherwise specified. Some data are further processed to comply with the data format of the LCA modelling.

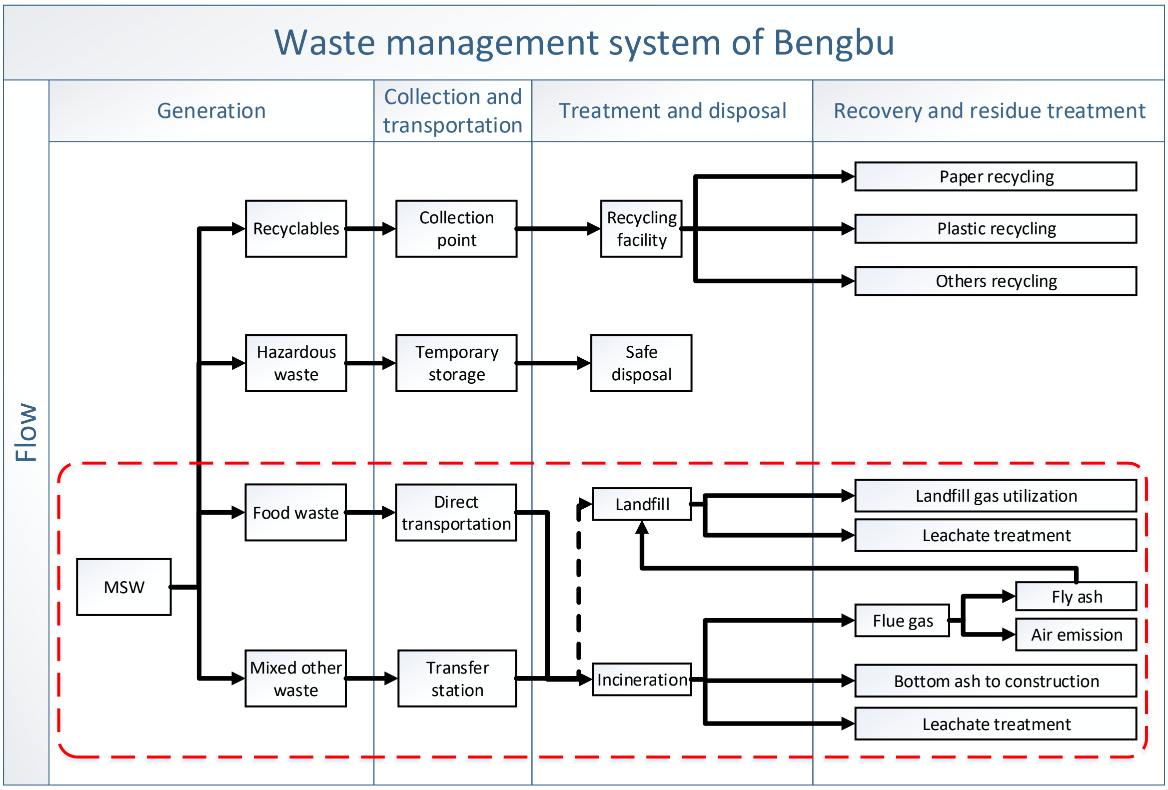


Figure 3.2: MSW system of Bengbu and system boundary in the current study (marked with a red dashed line)

3.3 Waste generation

The amounts of municipal solid waste are provided by the waste system managers as a total of both Mixed other waste and Food waste (Table 3.2). The amount of Food waste was determined separately in 2019, and assuming that the proportion of Food waste has been constant over the years, the amounts of Mixed other waste and of Food waste in 2015-2018 are calculated from the total amount presented in Table 3.2

Table 3.2: Amount of municipal solid waste including both Mixed other waste and Food waste in Bengbu.

Year	Total amount of municipal solid waste (t/y)
2015	2.96×10^5
2016	3.11×10^5
2017	3.14×10^5
2018	3.19×10^5
2019	3.21×10^5

Mixed other waste

The amounts and fractions of mixed other waste are listed in Table 3.3. The waste composition data are calculated from the routine monitoring per season in 2019, which does not involve Food waste collected separately. The composition data of 2015-2018 are not available.

Table 3.3: Amount and composition of Mixed other waste in Bengbu.

Year	Calculated amount of Mixed other waste	Material fractions of mixed other waste (% ww)							
	t/y	Paper	Plastic	Wood	Textile	Food waste	Metal	Glass	Others
2015	2.61×10^5	ND	ND	ND	ND	ND	ND	ND	ND
2016	2.74×10^5	ND	ND	ND	ND	ND	ND	ND	ND
2017	2.77×10^5	ND	ND	ND	ND	ND	ND	ND	ND
2018	2.81×10^5	ND	ND	ND	ND	ND	ND	ND	ND
2019	2.83×10^5	11.43	22.76	2.05	5.49	46.72	0.76	4.25	6.54

The data of waste characteristics are average numbers obtained from the routine monitoring in 2019. Data for 2015-2018 are not available.

Table 3.4: Physical characteristics of mixed other waste in Bengbu.

Year	Density	Water	TS*	VS	Ash	Lower Heating Value**
	kg/m3	% ww	%	%TS	%TS	kJ/kg TS
2015	ND	ND	ND	ND	ND	ND
2016	ND	ND	ND	ND	ND	ND
2017	ND	ND	ND	ND	ND	ND
2018	ND	ND	ND	ND	ND	ND
2019	ND	61.5	38.5	58.3	41.7	15470

** The numbers in the column "TS" are calculated from the numbers in the column "water".*

*** The monitored LHV is on the dry basis, and the corresponding LHV on wet basis is calculated as 5950 kJ/kg according to the water content.*

Table 3.5: Physical characteristics of mixed other waste in Bengbu.

year	Composition (%TS)										
	C	H	N	O	S	Cl	Cr	Cd	Pb	Hg	Sn
2015	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2016	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2017	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2018	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2019	39.11	5.51	1.48	32.55	0.20	0.29	3.12×10^{-3}	ND	1.12×10^{-4}	5.27×10^{-6}	ND

Food waste

Before 2019, the food waste was not separately collected or and its amount is unknown. As explained above estimates were made of the Food waste 2015-2018. The characteristics of food waste have not been measured.

From 2019, the food waste from restaurants is separately collected but still treated together with mixed other waste. Thus for 2019, the amount of Food waste is included in the amount of municipal solid waste presented in Table 3.2.

Table 3.6: Amount and characteristics of food waste in Bengbu.

Year	Amount*	Water	TS*	VS	Ash	Higher Heating Value	Proteins	Lipids
	t/y	% ww	%	%TS	%TS	kJ/kg TS	%	%
2015	3.50×10^{4}	ND	ND	ND	ND	ND	ND	ND
2016	3.68×10^{4}	ND	ND	ND	ND	ND	ND	ND
2017	3.72×10^{4}	ND	ND	ND	ND	ND	ND	ND
2018	3.77×10^{4}	ND	ND	ND	ND	ND	ND	ND
2019	3.79×10^{4}	ND	ND	ND	ND	ND	ND	ND

** The Food waste amounts in 2015-2018 are calculated from the Food waste amount in 2019 by assuming that the proportion of Food waste has been constant over the years.*

Hazardous waste and recyclables

Few data of hazardous waste or recyclables are available.

Table 3.7: Amount and composition of hazardous waste and recyclables in Bengbu.

Year	Hazardous waste amount	Recyclable waste amount	Recyclable waste fraction (% ww)				
	t/y	t/y	paper	plastic	metal	glass	others*
2015	ND	ND	ND	ND	ND	ND	ND
2016	ND	ND	ND	ND	ND	ND	ND
2017	ND	7030	99.57	0.43	ND	ND	ND
2018	396	16634	66.15	8.75	13.44	0.11	11.56
2019	ND	ND	ND	ND	ND	ND	ND

3.4 Collection, transfer and transportation

This section provides information about the collection, transfer and transport of Mixed other waste and of Food waste. Hazardous waste and recyclables are not dealt with.

Mixed other waste

The collection of the waste to the transfer stations involves small electrical vehicles (<1.5 t) and small diesel driven vehicles (3 t). The typical distance for collection vehicles is 2-3 km.

There were 19 transfer stations in Bengbu by the end of year 2018, with a total capacity of 1955 t/d. Two of them are large stations with a capacity of 500 t/d. Considering the overall amount of mixed waste generated, the daily amount of waste transferred is approximately 1200 t/d.

The transfer stations apply compression without any sorting of the waste.

The transportation from the transfer stations is by diesel driven trucks with a load of 8~10 t or in some cases even 18 t.

Data on the diesel consumption for the collection vehicles are reported in Table 3.8 and for the transportation vehicles in Table 3.9. The diesel-vehicle emission standard is GBIV/V.

Table 3.8: Diesel and electricity consumption for collection of mixed other waste.

year	Gross Vehicle Weight	Diesel consumption	Electricity consumption	Collection amount	Diesel consumption per ton of waste	Electricity consumption per ton of waste	Average collection distance
	t	L/y	kWh/y	t/y	L/t	kWh/t	km
2015	3/1.5	2.23×10^5	2.65×10^5	2.96×10^5	0.75	0.89	ND
2016	3/1.5	2.57×10^5	3.10×10^5	3.11×10^5	0.83	1.00	ND

2017	3/1.5	2.93×10^5	3.25×10^5	3.14×10^5	0.93	1.03	ND
2018	ND	ND	ND	3.19×10^5	ND	ND	ND
2019	ND	ND	ND	3.21×10^5	ND	ND	ND

Table 3.9: Fuel consumption for transport of mixed other waste.

year	Gross Vehicle Weight	Diesel consumption	Transport distance	Waste mount	Diesel consumption per ton of waste	Average transport distance	Diesel consumption per ton of waste per kilometer
	t	L/y	km	t/y	L/t	km	L/km·t
2015	8	6.15×10^5	ND	2.96×10^5	2.08	23.00	9.03×10^{-2}
2016	8	1.18×10^6	ND	3.11×10^5	3.80	24.00	1.58×10^{-1}
2017	8	1.25×10^6	ND	3.14×10^5	3.99	24.00	1.66×10^{-1}
2018	ND	ND	ND	3.19×10^5	ND	ND	ND
2019	ND	ND	ND	3.21×10^5	ND	ND	ND

The data of transfer stations are based on the reports from several typical transfer stations in 2019. The transfer stations are classified into small and large ones according to their capacity.

Table 3.10: Material and energy consumption of transfer stations.

Year	Scale	Transfer amount	Electricity consumption	Water consumption	Gas emissions	Waste water discharge	Unit electricity consumption	Unit water consumption
		t/y	kWh/y	t/y	m3/y	m3/y	kWh/t	kg/t
2015	ND	ND	ND	ND	ND	ND	ND	ND
2016	ND	ND	ND	ND	ND	ND	ND	ND
2017	ND	ND	ND	ND	ND	ND	ND	ND
2018	ND	ND	ND	ND	ND	ND	ND	ND
2019	Small	14000	14820	1000	ND	ND	1.06	71.43
	Large	66357	93607	6000	ND	ND	1.41	90.42

The destination of the mixed other waste is reported in Table 3.11.

Table 3.11: Destination of mixed other waste.

Year	Generation amount	To landfill	To incineration	Proportion to landfill	Proportion to incineration
	t/y	t/y	t/y	%	%
2015	2.96×10^5	2.96×10^5	0.00	100	0
2016	3.11×10^5	3.11×10^5	0.00	100	0
2017	3.14×10^5	3.14×10^5	0.00	100	0
2018	3.19×10^5	0.00	3.19×10^5	0	100
2019	3.21×10^5	0.00	3.21×10^5	0	100

Food waste

Restaurant waste is declared by the production units to the environmental sanitation department. After approval, Bengbu Wangneng Company sends vehicles to transport the restaurant waste to the treatment facility. No specific data on food waste collection and transportation are available.

The destination of the Food waste is the same as that of the Mixed other waste, as reported in Table 3.12.

Table 3.12: Destination of food waste (AD: anaerobic digestion).

Year	Amount	To AD	To landfill	To incineration	Proportion to AD	Proportion to landfill	Proportion to incineration
	t/y	t/y	t/y	t/y	%	%	%
2015	ND	ND	ND	ND	ND	ND	ND
2016	ND	ND	ND	ND	ND	ND	ND
2017	ND	ND	ND	ND	ND	ND	ND
2018	ND	ND	ND	ND	ND	ND	ND
2019	3.79×10^4	0	0	3.79×10^4	0	0	100

3.5 Bio treatment

Bengbu built its first AD plant close to the incinerator and landfill in 2019, with the purpose of treating the food waste separately collected from restaurants. The AD plant is managed and operated by Wangneng Company with a designed capacity of 200 t/d. The trail operation started in 2020, and currently no operational data are available.

The process concept is anaerobic digestion. Large impurities are removed after the food waste enters the treatment plant (technology not specified). Then oil in the waste is separated (technology not specified) and the waste oil is sold to external industry for biodiesel production. The food waste is then routed to anaerobic digestion which operates as a dry process. The generated biogas is sent to combined power and heat generation. The recovered electricity is sold to the grid and the heat is used internally to heat the digester. The digestate is planned to be composted but is sent to the incinerator located nearby after drying. The technology used in the AD plant is illustrated in Figure 3.3.

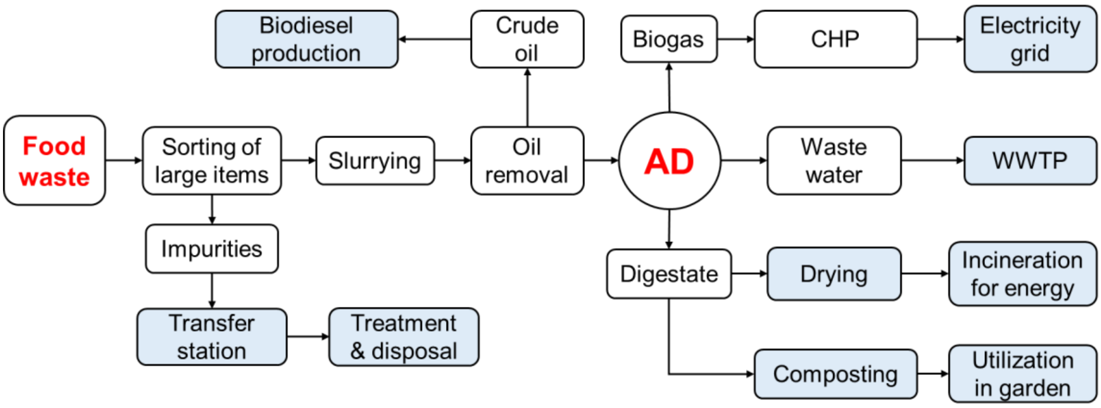


Figure 3.3: Flow chart of food waste treatment in AD (The blue boxes are implemented outside the AD plant)

The required technical data for inputs and outputs from AD are not available. In the current study, we use the data of unit energy and material consumption from an AD plant in Suzhou as listed in Tables 3.13. According to plans, the generated biogas is all utilized for electricity recovery as listed in Table 3.14.

Table 3.13: Material and energy consumption in the AD plant.

Unit energy and material consumption				Unit product recovery	
Electricity	Water	Diesel	Steam	Biogas	Crude oil
kWh/t	t/t	L/t	Nm3/t	Nm3/t	kg/t
11.9	4.07	0.00	0.00	87.43	23.67

Table 3.14: Biogas utilization in the AD plant.

CH4	Proportion to flare	Proportion to natural gas	Proportion to CHP
%	%	%	%
58	24.0	2.6	73.4

3.6 Incineration with energy recovery

The Bengbu MSWI was built in 2016 and is formally operated from 2018 by Green Power Company. The capacity of the grate furnace incineration plant is 1210 t/d. The incineration plant is equipped with a condensing steam turbine of 25 MW for electricity recovery. The plant is prepared for an additional capacity of 750 t/d for potential increase of waste amount in the future. The flue gas is treated by the air pollution control system, which includes semi-dry and dry gas treatment, selective non-catalytic NOx-removal, activated carbon injection and baghouse filter. The fly ash is landfilled after curing and the bottom ash is used for producing construction materials. The wastewater is treated in an inner WWTP and then reused.

The technical features of the incineration plant are described below in terms of energy budget for the plant, the air-pollution-control system, the ash management and the bunker leachate management.

Energy budget

The amount of diesel used in the upstart situations as well as the heat exported are presented in Table 3.15. The electricity budget is shown in Table 3.16.

Table 3.15: Material consumption and recovery in incineration of mixed other waste.

Year	Amount incinerated (at furnace entrance)*	Amount received (at bunker entrance)**	Diesel consumption	Heat generation as steam***	Unit diesel consumption	Unit heat generation as steam
	t/y	t/y	t/y	GJ/y	kg/t	MJ/t
2015	Not in operation					
2016						
2017						
2018	4.06×10^5	5.22×10^5	186.02	6.00×10^5	0.36	1148.98
2019	3.86×10^5	4.99×10^5	284.03	5.82×10^5	0.57	1167.34

** The amount of waste incinerated is provided by the incineration operators as the amount loaded to the furnaces rather than the amount received as wet waste.*

*** The amount received at the bunker entrance is calculated based on the incinerated amount and the leachate amount collected in the bunker. The sum of these values are higher than the Mixed waste amounts in Table 3.3 because the incineration plant also deals with waste generated in the suburb of Bengbu. The amount received at the bunker entrance is used to calculate the unit material and energy consumption and recovery, which is then normalized according to the amount in Table 3.3.*

**** The heat generation is in terms of steam, which is not for utilization.*

Table 3.16: Energy consumption and recovery in incineration of mixed other waste.

Year	Electricity recovery	Electricity exported*	Electricity consumption	Extra electricity consumption	Unit electricity recovery	Unit electricity export	Unit electricity consumption
	MWh/y	MWh/y	MWh/y	MWh/y	kWh/t	kWh/t	kWh/t
2015	Not in operation						
2016							
2017							
2018	1.85×10^{5}	1.57×10^{5}	2.75×10^{4}	57.54	353.96	301.30	46.90
2019	1.84×10^{5}	1.55×10^{5}	2.89×10^{4}	0.00	368.38	310.34	51.48

** Electricity export is the electricity transmitted to the local grid.*

Air pollution control

The flue gas emissions are presented in Table 3.17 and the materials used in the air-pollution-control system are presented in Table 3.18.

Table 3.17: Flue gas emission from incineration of mixed other waste.

Year	Flue gas emission amount	Flue gas concentration* mg/Nm3						Unit flue gas emission g/t waste					
	Nm3/y	PM	HCl	CO	SO2	NOx	Dioxin (TEQng/Nm3)	PM	HCl	CO	SO2	NOx	Dioxin (TEQng/t)
2015	Not in operation												
2016													
2017													
2018	1.11×10^{9}	0.40	8.80	9.60	22.00	178.00	6.80×10^{-3}	0.85	18.74	20.44	46.84	378.98	14.48
2019	1.23×10^{9}	0.50	7.60	10.00	23.00	171.00	7.60×10^{-3}	1.23	18.74	24.66	56.71	421.65	18.74

** The data on dioxins are not available.*

Table 3.18: Material consumption in air-pollution-control in incineration of mixed other waste.

Year	Material consumption (t/y)				Unit material consumption (kg/t)			
	Lime	Activated Carbon	Aqua ammonia (20%)	Demineralized water	Lime	Activated Carbon	Aqua ammonia (20%)	Demineralized water
2015	Not in operation							
2016								
2017								
2018	5.55×10^3	132.47	1266.48	7.30×10^5	10.64	0.25	2.43	1.40×10^3
2019	5.35×10^3	144.73	718.62	7.45×10^5	10.73	0.29	1.44	1.54×10^3

Bottom ash and fly ash

Bottom ash is sent for utilization as construction materials, but the data of utilization are not available. Fly ash (after chelate stabilization, technology not specified) is landfilled in the same landfill as the mixed other waste nearby, but the data on separately landfilling of the ash are not available.

Table 3.19: Bottom and fly ash in incineration of mixed other waste treatment.

Year	Bottom ash amount	Unit bottom ash amount	Fly ash amount	Unit fly ash amount	fly ash composition* (%TS)						Chelation consumption**	
	t/y	kg/t	t/y	kg/t	As	Cr	Pb	Cd	Zn	Hg	t/y	kg/t fly ash
2015	Not in operation				ND						Not in operation	
2016												
2017												
2018	1.14×10^5	219.31	1.33×10^4	25.56							288.00	21.59
2019	1.00×10^5	201.54	1.32×10^4	26.54							284.00	21.47

** The elementary concentrations from leaching test are provided, but the compositions of heavy metals in the fly ash are not available.*
*** The chelation with dithiocarboxyl, but details are not provided due to business confidence.*

Bunker leachate treatment

The leachate is collected from the bunker and treated by anaerobic digestion followed by UASB and (A/O) MBR process, and filtration (nano- and reverse osmosis). Material end energy consumptions are presented in Table 3.20 and calculated per ton of waste in Table 3.21. The bunker leachate concentrations before and after treatment are presented in Table 3.22 and 3.23 respectively.

The discharge emission from the treated bunker leachate is presented in Table 3.24.

Table 3.20: Material and energy consumption for leachate treatment in incineration of mixed other waste treatment.

Year	Leachate amount	Water recycling amount	Electricity consumption	Polyacrylamide	Hydrochloric acid *	Antiscale	Sodium hypochlorite	Citric acid	NaOH
	t/y	t/y	MWh/y	kg/y	kg/y	kg/y	kg/y	kg/y	kg/y
2015	Not in operation								
2016									
2017									
2018	1.16×10^5	8.59×10^4	3122.01	6.13×10^3	2.35×10^5	1.00×10^4	1.00×10^3	300.00	300.00
2019	1.13×10^5	8.41×10^4	3268.60	1.38×10^4	6.21×10^3	9.00×10^3	1.03×10^3	312.50	300.00

** The consumption of hydrochloric acid varies significantly in 2018 and 2019; data need to be double checked.*

Table 3.21: Unit material and energy consumption for leachate treatment in incineration of mixed other waste treatment.

Year	Unit material and energy consumption								
	Leachate amount	Water recycling amount	Electricity consumption	Polyacrylamide	Hydrochloric acid	Antiscale	Sodium hypochlorite	Citric acid	NaOH
	t/t	t/t	kWh/t	kg/t	kg/t	kg/t	kg/t	kg/t	kg/t
2015	Not in operation								
2016									
2017									
2018	0.22	0.16	5.98	1.17×10^{-2}	4.51×10^{-1}	1.92×10^{-2}	1.92×10^{-3}	5.75×10^{-4}	5.75×10^{-4}
2019	0.23	0.17	6.56	2.77×10^{-2}	1.25×10^{-2}	1.81×10^{-2}	2.06×10^{-3}	6.27×10^{-4}	6.02×10^{-4}

Table 3.22: Bunker leachate concentrations before treatment.

Year	Leachate concentration before treatment (mg/L)							
	CODCr	NH3-N	BOD5	TP	Cl-	TDS	TN	SS
2015	Not in operation							
2016								
2017								
2018	35780	1450	21468	55.6	8869	ND	1480	ND
2019	32895	1472	21300	57.4	8200	ND	1523	ND

Table 3.23: Bunker leachate concentrations after treatment.

Year	Leachate concentration after treatment (mg/L)							
	CODCr	NH3-N	BOD5	TP	Cl-	TDS	TN	SS
2015	Not in operation							
2016								
2017								
2018	9.00	3.25	2.20	0.03	ND	ND	ND	5.00
2019	8.00	3.37	2.10	0.07	ND	ND	ND	4.00

Table 3.24: Unit bunker leachate discharge from incineration of mixed other waste treatment.

Year	Unit leachate discharge* (mg/t)							
	CODCr	NH3-N	BOD5	TP	Cl-	TDS	TN	SS
2015	Not in operation							
2016								
2017								
2018	2.00	0.72	0.49	0.01	ND	ND	ND	1.11
2019	1.81	0.76	0.48	0.02	ND	ND	ND	0.90

** The unit leachate discharge in mg/t is calculated from the concentrations after treatment shown previously.*

3.7 Landfill

The Bengbu Sanitary Landfill opened officially in 2006. The designed capacity was 800 t/d and the length of service was designed as 16 years. The facilities of leachate treatment and landfill gas utilization were placed in service in 2009 and 2014, respectively. In the early stage, rain water infiltration and odor emission caused significant public nuisance. In 2015, advanced rain and leachate separation system and HDPE cover system were activated. The landfill stopped receiving fresh MSW from 2018 when the incinerator started its service.

The landfill operation included unloading, spreading, compacting and covering. The landfill was equipped with bottom liners of HDPE membrane and leachate collection system. From 2015, HDPE membranes were used for interim cover, and surface water runoff was controlled and kept separate from the leachate. Landfill gas was collected for electricity production from 2014. The leachate was preliminarily treated in a specialized treatment plant using UASB and SBR technology, and the treated water was discharged to sewage network for further treatment in WWTP.

Table 3.25 presents the materials and energy consumption at the landfill. Table 3.26 provides data on the landfill gas.

Table 3.25: Material and energy consumption in landfill for mixed other waste treatment.

Year	Landfill amount	Energy and material consumption (t/y)				Unit energy and material consumption (kg/t)			
	t/y	Energy (MWh/y)	Diesel	Biological agent *	HDPE	Energy (kWh/t)	Diesel	Biological agent *	HDPE
2015	2.96×10^5	4.91×10^2	83.24	6.34	ND	1.66	0.28	2.14×10^{-2}	ND
2016	3.11×10^5	7.45×10^2	130.04	ND	ND	2.39	0.42	ND	ND
2017	3.14×10^5	8.21×10^2	149.90	10.30	ND	2.61	0.48	3.28×10^{-2}	ND
2018	0.00	7.37×10^2	63.83	2.00	ND	ND	ND	ND	ND
2019	0.00	3.93×10^2	42.77	0.00	ND	ND	ND	ND	ND

** The biological agent is not specified.*

Table 3.26: Landfill gas in landfill for mixed other waste treatment.

Year	Collected amount	Amount for energy recovery	Flare	Energy recovery*	Energy recovery rate	Landfill gas fraction (%volume)					
	m3/y	m3/y	m3/y	kwh/y	kwh/m3	CH4	CO2	SO2	VOC	H2S	others
2015	4.25×10^6	4.25×10^6	ND	7.56×10^6	1.78	52.00	ND				
2016	8.63×10^6	8.63×10^6	ND	1.24×10^7	1.44	52.80					
2017	1.08×10^7	1.08×10^7	ND	1.51×10^7	1.40	50.00					
2018	1.06×10^7	1.06×10^7	ND	1.49×10^7	1.40	ND					
2019	4.74×10^6	4.74×10^6	ND	6.64×10^6	1.40	31.93					

Tables 3.27 provides data on the material and energy consumption in leachate management and Table 3.28 provides the pollutant concentrations after leachate treatment.

Table 3.27: Leachate before treatment in landfill for mixed other waste treatment.

Year	Leachate amount	Energy and material consumption (t/y)					Unit energy and material consumption (kg/m3)				
	t/y	Energy (MWh/y)	Glucose	NaHCO3	NaOH	HCl	Energy (kWh/m3)	Glucose	NaHCO3	NaOH	HCl
2015	9.67×10^4	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2016	1.15×10^5	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2017	1.10×10^5	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2018	1.09×10^5	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2019	1.12×10^5	1.11×10^3	18.67	11.45	9.87	10.68	9.87	0.17	0.10	0.09	0.10

Table 3.28: Leachate after treatment in landfill for mixed other waste treatment.

Year	Leachate concentration after treatment (mg/m3)												
	COD	NH3-N	TN	TP	As	Cr	BOD5	Cr6+	Hg	Cd	Pb	SS	E. coli (Num)
2015	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2016	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2017	5.85×10^4	6.80×10^3	1.15×10^4	1.70×10^2	L*	L	1.62×10^4	L	L	L	L	1.00×10^4	1.30×10^6
2018	7.21×10^4	7.90×10^3	2.31×10^4	6.12×10^2	L	L	2.13×10^4	L	L	L	L	1.60×10^4	8.40×10^6
2019	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

** The letter 'L' means the concentration of the specific element is lower than its detection limit.*

4 LCA modelling of the Bengbu waste management system

This section describes in an overview the LCA modelling of the Bengbu waste management system. The specification of the LCA approach was presented in chapter 2, the data collected about the Bengbu waste management system were presented in chapter 3 and the detailed technical information about the LCA-modelling in terms of assumptions and data are found in Appendix. This chapter introduces the interested reader to how the modelling is done, while the expert reader is referred to the Appendix for specific details. The following items are included:

1. Defining the system
2. Waste
3. Waste technologies
4. Energy technologies
5. Scenarios modelled
6. Robustness assessment
7. Quality controls
8. Main results
9. Discussion
10. Conclusions

4.1 Defining the system

The LCA modelling of the Bengbu waste management system deals with two waste types:

- Mixed other waste which is the waste discarded by the citizen after recyclables have been removed for handling by the informal sector or specific companies and hazardous waste has been removed for special treatment.
- Food waste which is waste generated by restaurants, cantinas and markets

The modelling is done separately for the two waste types since they are separate sources and potentially have separate collection and treatment systems. The two waste types or fractions of them maybe treated in the same technical facilities.

Recyclables collected and managed by the informal sector or by registered companies are not included since very little information is available about the management of the materials and how they are recycled. Hazardous waste is likewise not included since hazardous waste is a very small fraction of household waste and follows a separate management system.

Materials like paper and plastic present in the Mixed other waste – that means after recyclables have been removed by the informal sector and by registered companies – are not considered suitable for recycling. Only the food waste in the Mixed other waste is considered suitable for source separation and recycling.

The modelling of the technical waste system includes:

- The waste at the point of collection
- Collection, transfer and transport
- Treatment of all fractions and residues at different facilities
- Consumption of materials, fuels and energy within the waste management system
- Direct emission from the waste management system
- Benefits obtained from recovering materials, fuels and energy from the waste management system

The resources used and environmental aspects of building and maintaining the system are not included in the model.

The modelling includes 4 time periods:

- BASELINE: 2015-2017 representing the waste management system prior to the start of the China IWM NSP program
- CURRENT: 2018-2019 representing the current MSW system for which we have a significant amount of actual data
- PLANNED: 2020-2025 representing the MSW system as expected according to the five-year-plan and relevant government documents
- FUTURE: 2025-2035 representing a hypothetical future MSW system with a high environmental focus

The modelling addresses the four time periods separately and does not provide detailed modelling of the transitions between the time periods. The characteristics of the 4 periods are presented later.

The population as well as the amount of waste generated per person may develop over the full time period considered (2015-2035), which may complicate the interpretation of the results as to which technical systems causes which environmental impacts. In order to improve the comparison of the system performance over time we have chosen to model 1000 tons of each waste type. The waste composition for the BASELINE and CURRENT are assumed the same on the basis of actual data in 2019 (Appendix explains how the data were obtained). While we have generated a waste composition for the last two periods (PLANNED: 2021-2025 and FUTURE: 2025-2030) assuming trends in consumer patterns regarding plastic and food waste.

Since the modelling is linear in the amount of waste considered, estimated environmental impacts can easily be scaled to actual annual amounts of waste.

Data from Bengbu has been used to the extent possible, but in some cases it has been necessary to supplement with data from other Chinese studies and from general data available in the EASETECH databases. This is described further below where relevant.

Quantifications of the environmental impacts associated with consumption of materials as well as recycling of materials are obtained from Ecoinvent databases, using Chinese data to the extent possible. The quantifications are considered constant over the period (2015-2035). The fuel and energy consumed and recovered are represented by Chinese data and are constant through all periods. However, future greener energy systems are considered in the scenario analysis regarding the FUTURE period. This is described later.

4.2 Waste

Mixed other waste

The 1000 tons Mixed other waste considered are physically scattered over the city as no statistical data on its distribution among districts are available. Thus, the transportation distance is modelled as an average distance.

The composition of the Mixed other waste in terms of material fractions have been defined as an average of actual data from Bengbu. The composition is shown in Table 4.1. In the LCA model the composition of the waste is actually represented by 8 fractions (Appendix, Table A3). The future waste composition is expected to include more plastic and less household food waste as reflected in the data presented in Table 4.1.

Table 4.1: Composition of Mixed other waste, % of wet weight

Fraction	Unit	Scenario		
		BASELINE/CURRENT	PLANNED	FUTURE
paper	%	11.4	12.0	12.0
plastic	%	22.8	25.0	28.0

garden waste	%	2.05	2.0	2.0
textile	%	5.5	5.0	5.0
household food waste	%	46.7	45.0	42.0
metal	%	0.75	0.8	0.8
glass	%	4.25	4.0	4.0
others	%	6.55	6.2	6.2

The moisture content of the Mixed other waste is high (61.5% in BASELINE and CURRENT). In the modelling the moisture content is distributed among the 8 material fractions in the waste: The distribution of the water among the fractions is balanced according to the monitored overall water content and to the best of our knowledge about water content of waste material fractiosn. In particular, the household food waste fraction is very wet containing 90% water based on the calculations.

The chemical composition of the material fractions - all elements are tracked throughout the waste system - is found in Appendix, Table A4. The data of some elements including C, H, N, O, S, Cl, Cr, Pb and Hg are balanced according to the monitored data from Bengbu. The data of most other elements are of European origin but considered appropriate for Chinese waste given the similar products contained in the same fraction. A critical parameter influencing the Climate change impacts of the waste management is the amount of carbon and its distribution between biogenic and fossil origin. In BASELINE and CURRENT, the Mixed other waste contain 0.16 kg C/kg wet waste and 41% is of biogenic origin while 59% is of fossil origin. These distributions were calculated based on the material fractions present in the waste. The estimated distribution between biogenic and fossil carbon does differ somewhat from what has been observed in Europe, where the biogenic carbon usually dominates. This issue may need to be addressed further in the future.

Food waste

The 1000 tons Food waste considered are physically scattered over the city as we have no specific information about actual collection points. The Food waste is collected separately from the Mixed other waste but still treated in the same facilities. Thus, the transportation distance is modelled identical to that for the Mixed other waste.

Since no composition information of Food waste in available in Bengbu, the data used in the modelling are taken from Suzhou. The Food waste is one fraction and characterized by a high water content of 77%. Of the dry matter (TS) 91% is volatile solids and 9% is ash. Details in Appendix, Table A4.

The actually collected Food waste likely contains some unwanted and misplaced items (impurities), and at the treatment facilities, these items will be removed as the first step in the processing. Since no detailed information about the impurities are available, it is assumed in the modelling that the food waste is void of impurities. This could lead to a slight overestimation of the amount of food waste treated.

4.3 Waste technologies

Collection, transfer and transport

Waste collection for Mixed other waste is defined as collection from several collection points by a diesel or electric vehicle and driving to a transfer station. This is modelled in terms of a fuel or electricity consumption per ton of waste collected; based on data from Bengbu around 0.84 L of diesel and 0.98 kWh of electricity are used per ton of Mixed other waste in average.

The transfer of Mixed other waste at transfer stations is modelled in terms of the power consumptions for the reloading and compacting the waste; the average value is 1.06 kWh per ton Mixed other waste for small transfer stations and 1.41 kWh per ton for large ones.

The transportation from the transfer station to the treatment facility is modelled by the fuel consumption per km and ton and thus reflects the distance travelled to the facility where the truck unloads. The value used is based on data from Bengbu: 0.16 litre diesel per km and ton. The same value is used for both Mixed other waste and Food waste transportation since they are currently transferred and transported in a mixed way.

The fuel consumption is associated with emission standards for diesel trucks. EASETECH uses EURO standards in the conversion of the fuel consumption into emission. We use EURO IV for the BASELINE and CURRENT, EURO V for the PLANNED time periods, and EURO VI for the FUTURE; we believe these standards are matching fairly well the corresponding Chinese standards for diesel exhaust.

Landfilling

Data from the Bengbu landfill has been collected and used to assist in estimating the key parameters for landfilling of one unit of Mixed other waste. The inventory for landfilling of waste includes all the consumptions and emission for the following 100 years. The landfill module contains several subunits:

- Estimates of the gas generation over time paying attention to the composition of the organic part of the waste and the landfill environment in terms of temperature and moisture content. The content of organics in waste is defined by the waste landfilled, while the degradation parameters are from the literature. Carbon of biogenic origin which is not converted to landfill gas or leached out within the 100 year period considered is defined as unavailable and quantified as stored carbon constituting a saving with respect to climate change impacts.
- Estimates of the efficiency of gas collection over a 100 year period matched with varying use of gas control and utilization technology over time; this includes membranes, top covers, gas combustion combined with a turbine, gas flaring and gas oxidation in top covers. Most of these parameters are expert judgement supplemented with knowledge about how the landfill currently operates in terms of filling depth, covers and gas technology installed.
- Estimates of the trace composition of the landfill gas are based on literature information and European data. We have not found available Chinese data.
- Estimates on leachate generation per ton of waste landfilled for 100 years. This is done paying attention to current use of liners and top covers, the filling depth and the precipitation patterns in the area. The estimated leachate generation was balanced with the data on amount of collected leachate. It is assumed that all leachate generated is collect and treated, except for the last 20 years where it is assumed that 13% of the leachate migrates out of the landfill and reaches surface waters.
- Estimates on the composition of the leachate over time: this is partly supported by data from monitoring of current leachate at the landfill and experiences from European and American landfills supplemented with leaching test.
- Estimates on the efficiency of the leachate treatment prior to discharge of the treated water to surface waters. Data from the current leachate treatment plant plays a role here.
- The details about the modelling of the landfill can be found in Appendix. In summary the modelling of the landfilling of 1000 tons of Mixed other waste involves in the BASELINE time period:
- 6.2×10^4 m3 of landfill gas of which 61.5% is utilized for electricity production, 2.7% is flared, 0.0% naturally oxidized and 35.8% escapes to the atmosphere.
- approximately 49.0% of the biogenic carbon landfilled is still present in the landfill after 100 year.
- 350 m3 of leachate which is discharged to surface water after treatment where 98.3% of COD is removed and trace components are assumed reduced by 70-95% for most elements.

The landfilling of the ash from the incinerator is assumed to generate no gas, while leachate data were taken from an existing EASETECH module for a mineral landfill. This includes treatment of the leachate. The energy consumption is accounted for as well.

Incineration

The incinerator is modelled based on data from the actual incinerator in Bengbu with regard to the material consumption, the energy and fuel uses and energy recovery. Data on actual flue gas emission are also included.

The incineration module employs waste-specific emission and process specific emissions; the former is expressed as a fraction of the content of the waste incinerated, while the latter is specified as an amount per ton of waste incinerated independent of the composition of the waste. The process specific emissions are emissions primarily controlled by the operation of the plant and/or by emission standards and includes carbon monoxide, dioxins, hydrochloric acid, nitrous oxides, sulphur dioxide and particulate matter > 10 um.

The datasets established are based on datasets from similar technologies adjusted to actually measured emission at the Bengbu incinerator. Priority has been given to a proper balancing of the energy issues and the direct emission, while amounts and composition of the bottom ash and the APC-residues have been of less importance.

In addition to the flue gas emission through the stack, the incinerator has physical outputs in terms of:

- Leachate from the waste bunker. This is treated and partly reused in the plant.
- Bottom ash from the furnace. This is upgraded and used as aggregates in road construction where it substitutes for rock-based aggregates.
- APC-residues in terms of ashes from the air-pollution-control. This enters into an ash landfill. We assume no emissions of gas while leachate is treated prior to discharge. The energy consumptions are accounted for.
- The energy budget of the incinerator is crucial in assessing its environmental performance; this includes:
- Electricity used for running cranes, blowers, mechanical parts, fans etc.
- Diesel or gas used for upstart of the furnace.
- Electricity recovered for external use
- Heat recovered for external use

The Bengbu incinerator does not use any auxiliary coal for supporting the combustion process.

While the uses of energy are process specific, meaning a fixed value per unit of waste incinerated, the output of energy is related to the lower heating value of the waste incinerated. The recovery ratios of electricity and heat were based on the actual energy recovery in terms of the lower heating values; for the CURRENT and PLANNED periods 25.2% for electricity recovery and no heat recovery (potentially maximum 22.4% for heat recovery). For FUTURE we assume of 25.8% for recovery of electricity similar to the high electricity recovery reported by the Suzhou incinerator and (if possible) 22.4% for recovery of heat to be used externally if relevant technology improvement is implemented.

Biorefining/anaerobic digestion

The Food waste and potentially also the household food waste fraction separated from Mixed other waste can be treated in a biorefinery focused on anaerobic digestion.

The biorefinery may contain the following units:

- An initial screening and removal of impurities unwanted in the following process steps. We do not have data about the amount of impurities in the waste flows and thus neglect their presence and assume that the waste fraction is clean.
- Separation of fat and oil for production of biodiesel. We assume that 50% of the fat content of organic waste can be separated, partly based on data from Suzhou. If used directly as an industrial fuel, further upgrading is minimal, while use in engines require further upgrading and esterification. The diesel production is primarily characterized by energy and enzyme consumption.
- Anaerobic digestion producing a gas containing methane and carbon dioxide. This is modelled as a percentage conversion of the anaerobically digestible content of the individual organic fractions. The anaerobic digestion has an electricity consumption for handling and mixing.
- The gas can be used in a combustion engine or an incinerator combined with a turbine to produce electricity and potentially heat. Currently the gas is planned to be incinerated in a sludge incineration plant in Bengbu.

- The digestate, which is the left over after the digestion, is separated in to a liquid and a solid. The liquid is treated in a wastewater treatment plant, while the solid is routed to the incinerator for combustion.
- From an energy point of view, the critical aspects of the biorefinery are:
- Amount of electricity used in the plant.
- Amount of biodiesel recovered.
- Amount of gas produced and its conversion to electricity (we include the emission from the combustion of the gas, but credit the system for savings in electricity production).
- Amount of electricity used in the wastewater treatment plant.
- Any net energy recovered in incinerator from combusting the solid residue.

In terms of the climate change impact, in addition to the above-mentioned energy issues, also the fugitive loss of methane at the plant is important. This is set to 2.6% according to relevant studies in literature, as no actual data are available.

Based on the data available in a similar AD plant in Suzhou, we estimate that the gas produced in AD plant in Bengbu correspond to 75% of the potential gas generation in the PLANNED period. In FUTURE period we expect 80% of the potential gas generation for the improved AD plant.

4.4 Energy system

The Chinese energy system is undergoing dramatic changes as China moves towards a greener and more renewable energy system. In the report “China 2050 High Renewable Energy Penetration Scenario and Roadmap” published by Energy Research Institute of National Development and Reform Commission, a scenario with ideal development of society, policy, economy and technology was introduced to predict the energy structure up to 2050 under the demand of sustainable growth and carbon emission reduction. Figure 4.1 showing primary energy in terms of ton-coal-equivalents indicates that the total energy consumption will peak around 2025 and that renewable energy will increase its contribution significantly. However, by 2050 fossil-based energy still constitutes about 25-30% of all primary energy consumed.

The specific development of the Chinese energy system will be decided as part of the 5-year plans and the role of the waste-based energy determined as part of the development plans. Thus, currently there is no approach to predict what the waste-based energy will substitute except what can be argued by the Chinese ambition of reducing the contribution of fossil-based energy. Thus we assume in the modelling reaching as far as 2035 that the waste-based energy will substitute for fossil-based energy:

- Electricity: coal based (Ecoinvent database: electricity, high voltage electricity, high voltage, production mix, CN-JS) showing a GWP of 1.0 kg CO2-eqv./kWh.
- Heating: natural gas (Ecoinvent database: natural gas, low pressure, market for natural gas, low pressure, RoW) showing a GWP of 12.4 kg CO2-eqv./1000MJ (0.49 kg CO2-eqv./m3).
- Biodiesel: diesel (Ecoinvent database: diesel, low-sulfur, diesel production, low-sulphur, petroleum refinery operation, RoW) showing a GWP of 11.5 kg CO2-eqv./1000MJ (0.53 kg CO2-eqv./kg).
- Methane: natural gas (Ecoinvent database: natural gas, low pressure, market for natural gas, low pressure, RoW) showing a GWP of 12.4 kg CO2-eqv./1000MJ (0.49 kg CO2-eqv./m3).

We suggest that in a scenario reaching beyond 2035 that also substitution of wind power is considered, since wind power seems to be a dominant renewable energy source by 2050.

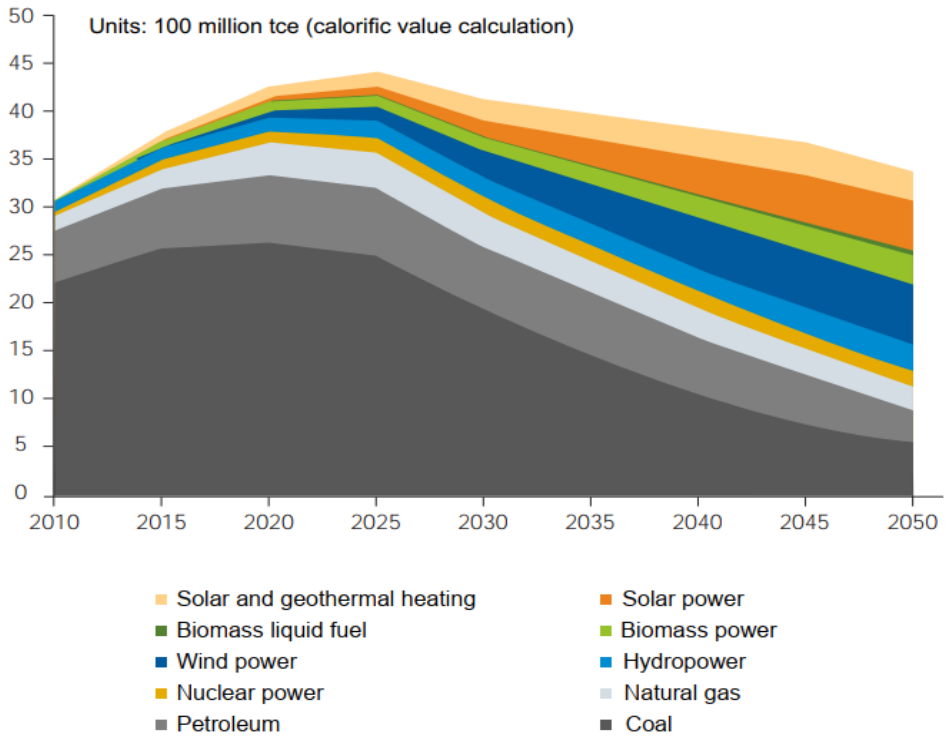


Figure 4.1: Development of primary energy in China in terms of ton-coal-equivalents

4.5 Scenarios

The characteristics of the 4 periods considered in terms of waste, technology and energy substitution are presented in Table 4.2. The main waste flows involved in the four scenarios are shown in Figure 4.2. The routing of the waste differs among the scenarios according to actual statistics and available capacities of the individual plants.

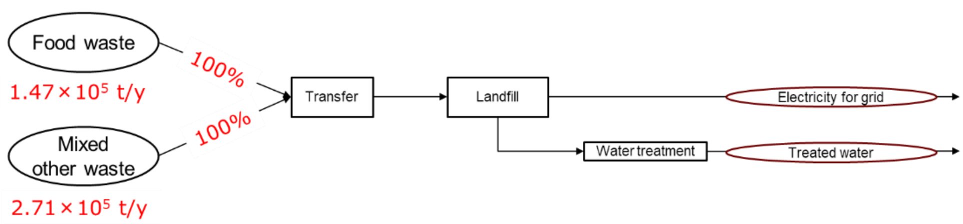
Table 4.2: The characteristics of the 4 periods considered in terms of waste, technology and energy substitution

Scenarios	BASELINE	CURRENT	PLANNED	FUTURE
Year	2015-2017	2018-2019	2020-2025	2025-2035
Waste				
Mixed other waste				
Reference flow	1000 tons			
Waste amounts	Actual	Actual	Forecasted (3.02×10^5 t/y)	Forecasted (3.47×10^5 t/y)
Fraction	As it is		Plastic increased, household food waste decreased	
Food waste source separation	No		Yes	

Food waste separation efficiency	Zero		Low (8% of household food waste)	Medium (20% of household food waste)
Food waste				
Reference flow	1000 tons			
Waste amounts	Actual	Actual	Forecasted (4.06×10^4 t/y)	Forecasted (4.66×10^4 t/y)
Composition	Constant as in Appendix Table A4			
Technology				
Collection and transport	EURO IV		EURO V	EURO VI
Landfill technology	As in Appendix	Landfill only for inert residues		
Landfill capacity	As reported	No limit for inert residues		
Biorefinery AD	Not established		As in Appendix	Improved performance (biogas generation ratio 80%)
AD capacity	Zero		As reported (100t/d)	No limit
Incinerator	Not in operation	As in Appendix		Improved performance (electricity recovery ratio 25.8%)
Incinerator capacity	Not in operation	As reported		No limit
Energy substitution				
Electricity	Production mix in Anhui, mainly coal based			
Heat	Heat from industrial steam			
Biodiesel	Diesel			

The actual modules employed in the modelling of the scenarios are found in the Appendix, Figures 2-7.

Baseline (2015-2017)



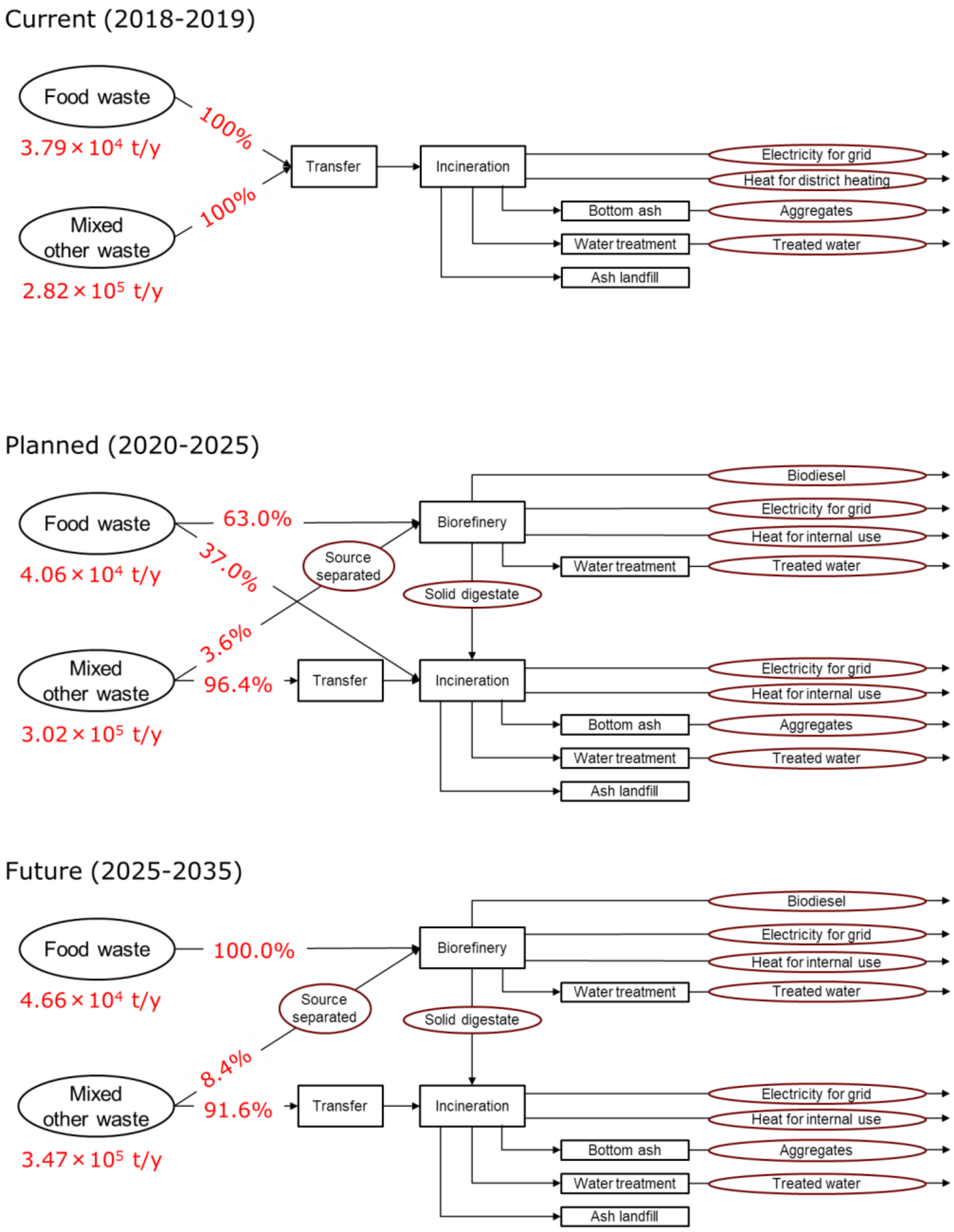


Figure 4.2: Flows of waste in the four scenarios: BASELINE, CURRENT, PLANNED and FUTURE

4.6 Robustness assessment

The robustness assessment addresses parameter sensitivity and scenario sensitivity.

Parameter sensitivity

In order to determine the robustness of the modelling we have conducted parameter sensitivity analysis for the PLANNED time period. Table 4.3 lists the variable parameters used for sensitivity analysis during the modelling. The parameters may vary due to statistical variance, technological deviations and uncertainty of data sources. Sensitivity ratios are calculated to quantify how the variation of a single parameter affects the overall results. We have done this with respect to parameters crucial for climate change potential. Parameters with high sensitivity ratios are important parameters.

Scenario sensitivity

In order to investigate the result variation due to potential options in strategy, technology and background energy, we have conducted scenario sensitivity analysis for the FUTURE time period which is the most uncertain one. Given that the potential options mainly are related to energy or energy product, only climate change impacts are reported in the scenario sensitivity analysis. The scenario assignments involved in scenario sensitivity are listed in Table 4.4. The details on biogas upgrading technologies and background energy processes are available in the Appendix.

Table 4.3: Variable parameters included in the sensitivity analysis of waste system in Bengbu

Technology	Sub-process	Parameter to be included and tested for sensitivity
Collection and transportation	Collection	Unit petrol consumption
	Transfer stations	Electricity consumption
	Transportation	Unit petrol consumption
	Distribution to facilities	Separation ratio of household food waste
Waste to energy (general)	Waste to energy plant	Electricity recovery
		Electricity consumption
		Activated carbon consumption
		Ammonia consumption
		As, Cd, Cr and Hg emissions in flue gas
		Emissions including particulates, NOx, SO2 and dioxins
	Leachate treatment	Electricity consumption
		Ancillary materials consumption
Anaerobic digestion (general)	Oil separation	Electricity consumption
	Biodiesel production	Amount of diesel substituted
		Electricity consumption
		Methanol consumption
		Enzymes consumption
	Solid separation	Transfer coefficients for water, TS, VS, ash, C, H, energy and other elements
	Anaerobic digestion	Biogas yield
		Electricity consumption

	Addition of substances	Ammonia
	Waste water treatment	Electricity consumption
	Biogas distribution	% flare, % loss, % utilization
	Stationary engine	Electricity recovery ratio

Table 4.4: Scenario assignments (16 individual scenarios) included in the scenario sensitivity analysis of waste system in Bengbu for the FUTURE time period.

A	B	C	D
Strategy	Technology		Background energy
Source separation ratio of food waste	Heat recovery in incinerator	Improvement in AD	Background electricity and heat
20%	0%	CH_4 loss: 2.6% Biogas yield: 80%	Electricity: mix based on coal Heat: steam from industry
15%	11.2%	CH_4 loss: 1.5% Biogas yield: 80%	Electricity: natural gas Heat: heavy oil
25%	22.4%	CH_4 loss: 2.6% Biogas yield: 85%	Electricity: hydro Heat: natural gas
30%	33.6%	CH_4 loss: 1.5% Biogas yield: 85%	Electricity: wind Heat: biomass

In Bengbu, it has recently been proposed to build a sorting facility. In order to address this we have introduced an additional scenario named FUTURE# as part of the scenario sensitivity analysis. In the additional scenario FUTURE#, a large sorting facility is built to facilitate the sorting of mixed other waste, as an alternative to source separation. The sorting facility is expected to focus on separation of household food waste to AD, while some recyclables including paper, plastic, metal and glass are sorted for external recycling. The residues are sent to the incinerator. Information about design parameters and expected performance are not available forcing us to use data from another Chinese plant although we do not know the actual set-up and technologies to be employed in Bengbu. The preliminary key data used in modelling this facility are listed in Tables 4.5-4.7; more details are available in the Appendix.

Table 4.5: Material and energy consumption in the mechanical sorting facility*.

Electricity	Water
kWh/t	t/t
5.44	0.114

** The numbers refer to the large mechanical sorting facility in Beijing from literature (Wang et al., 2013).*

Table 4.6: Transfer coefficients of relevant fractions to outputs in the mechanical sorting facility.

Fraction	Output (%)					
	Organic waste	Paper	Plastic	Metal	Glass	Residue
Food waste	70	0	0	0	0	30
Paper	0	30	0	0	0	70
Plastic	0	0	20	0	0	80
Metal	0	0	0	70	0	30
Glass	0	0	0	0	70	30
Others	0	0	0	0	0	100

Table 4.7: Recycling and substituting proportions of recycled fractions.

	Recycling proportion (%)	Substituting proportion (%)
Paper	91	90
Plastic	97	90
Metal	87	100
Glass	100	100

We do not have any information about the purity and quality of the recyclables recovered by the sorting plant

4.7 Quality controls

The LCA modelling of the Bengbu waste management system is based on a physical and technical representation of the actual waste management system to the extent that available data has made it possible. In some cases it has been necessary to supplement with theoretical and experienced based information in order to model all flows, emissions and energy exchanges. Since the waste and the facilities are scattered around the city and many emission are dispersive, it is not possible to assess the overall inventory data against measurements. Likewise, the impact assessment, which is based on standardized general impact assessment methods, for example in terms of an estimate of the potential climate change impact, cannot be compared to any measurements. This conceptual difficulty together with the fact that modelling involves hundreds of parameters and thousands of data makes quality control both very needed but also difficult to implement.

The following quality controls have be implemented:

1. Local data: The available local data have been compiled and summarized in section 3. The data have been scrutinized by two individual experts for consistency in units, values and balances where possible. This has created doubt about some of the collected data (as marked in the report) and attention to this has been exercised in our calculations of average data

used in the modelling, while excluding a few inconsistent data. Data has also been compared to experiences from similar data from other studies performed, and the data used are therefore screened data, that fulfil the data quality requirements for a robust modelling.

2. Scenarios: The general approach to the scenarios of the four time periods has been defined in collaboration among the universities, the city and GIZ. The actual modelling of the scenarios in terms of flows defined and processes involved has been decided by three senior experts in consensus. The flows have been set up by one senior experts and checked by two other experts.
3. Technologies: The technologies used are in most cases modifications of existing, quality assured technologies in EASETECH. The modification paying attention to local data have been made by two experts. In a few cases more experts have been involved in the process.
4. Results: The output in terms of waste flows, energy budgets, inventories and impacts have been assessed by at least three experts using their experience from previous studies and with focus on issues that by experience are considered crucial for the overall outcome of the study: Are the flows reasonable? Does the performance of the landfill resemble previous studies? Are unusual results explainable and are the data behind reasonable? etc. This quality control is an iterative process: In the early phases focus is on flows and energy, then climate change impacts is scrutinized, followed by assessing sensitive issues identified in the sensitivity analysis, and finally all impacts are assessed as to how significant the impact is and to determining factors.

5 Results of the LCA modelling of the Bengbu waste management system

The results of the LCA modelling are presented in details in Appendix Tables A57-A75 and summarized in this chapter.

5.1 Mixed other waste

The management of Mixed other waste is a net load to Climate change (34 tons/1000 tons) in the BASELINE time period primarily due to the load from the landfill. Because of the efficient landfill gas collection and carbon storage, the load from the landfill is at a moderate level. In contrast, in the CURRENT and PLANNED time periods where no Mixed other waste goes to landfill, the waste management constitutes a more significant load in Climate change (CURRENT: 60 tons/1000 tons, PLANNED: 58 tons/1000 tons). Incineration of the Mixed other waste constitutes loads in Climate change because significant fossil CO_2 emissions from plastic incineration and relatively low savings from household food waste incineration. In the FUTURE time period employing household food waste separation, less waste is incinerated and we assume a better performance of incineration as well as anaerobic digestion. This decreases the load to climate change to 44 tons/1000 tons. The loads from collection and transport are also important. This is shown in Figure 5.1

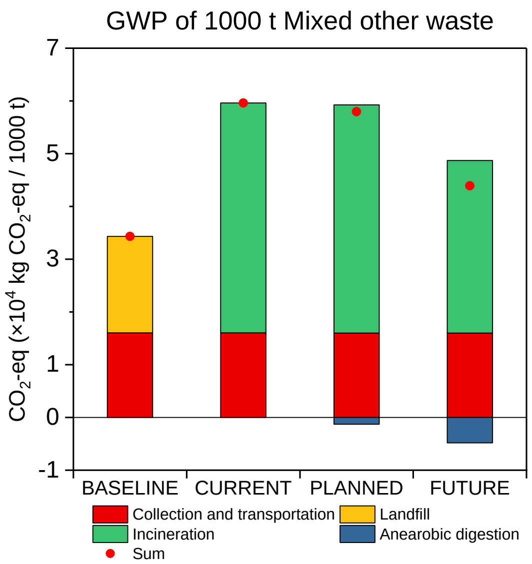


Figure 5.1: Overall climate change impacts as kg CO2-eqv. per 1000 tons of wet Mixed other waste in four time periods

Figure 5.2 shows loads and savings for each main technology with respect to the climate change impacts of managing 1000 tons wet Mixed other waste in the four time periods. This shows that incineration has significant loads as well as significant savings in the order of 400 tons CO_2-eqv. per 1000 tons Mixed waste. Overall, incineration constitutes a slight load in climate change in all scenarios except the BASELINE period, where the incinerator was not in operation. This phenomenon is different from the incinerator of Suzhou, though the energy recovery ratios of the two plants are comparable relative to their lower heating values. The load to climate change is from combustion of fossil materials in the waste (primarily plastics) and from running the plant (primarily electricity). However, the mixed waste in Bengbu contains less household food waste and more non-combustible fractions (ash and glass), which means less biogenic carbon and lower heating value. In this case, the savings from the produced electricity substituting for fossil-based electricity cannot fully outbalance the loads. Therefore, the climate change impacts of incinerating Mixed other waste is a slight load although of only of the order of 40 tons CO_2-eqv. per 1000 tons Mixed waste.

In general, collection and transport is a net load in all scenarios with respect to climate change due to the use of fossil transport fuels and it does not change per 1000 tons of waste over time. Some electric vehicles are being used for waste collection in Bengbu: their relevant impacts are integrated in those from energy consumption in the transfer station and require further evaluation with consideration of gradually replacing fossil fuel vehicles.

The landfill was in operation only in the BASELINE period. The load is mainly from methane escaping the from the landfill, while the savings are from energy produced and from storage of biogenic carbon longer than 100 years as is the time horizon considered.

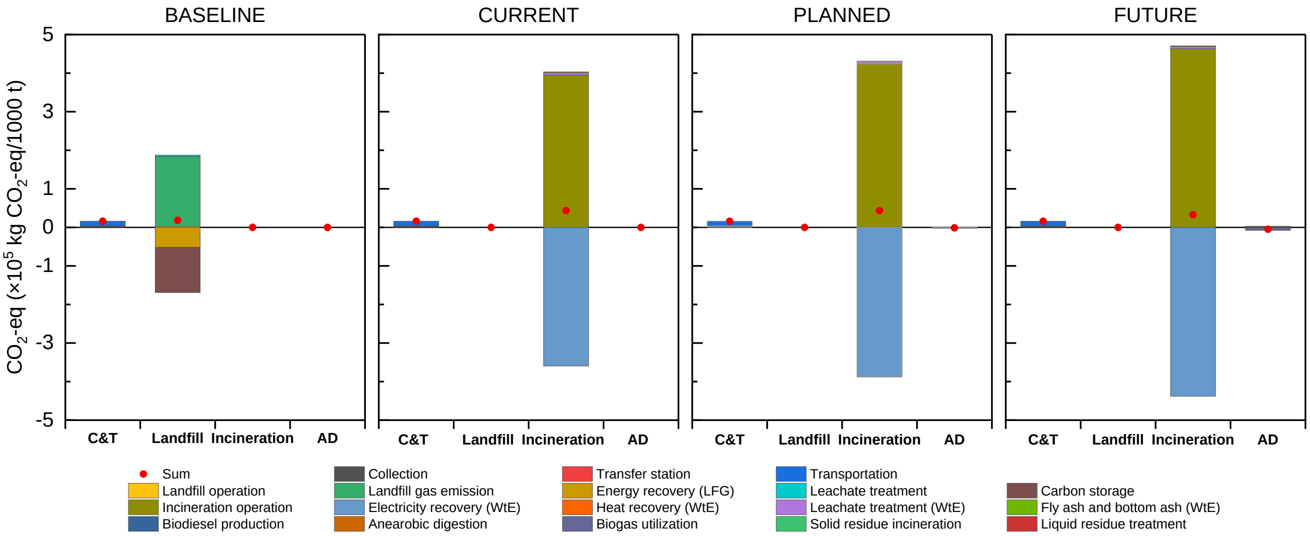


Figure 5.2: Process contribution of climate change impacts as kg CO2-eqv. per 1000 tons of wet Mixed other waste in four time periods

The biorefinery based on anaerobic digestion was not involved in the BASELINE and CURRENT periods. In the later time periods biorefining of food waste showed savings with the compulsory requirement of source separation of household food waste from mixed waste. The impacts of the biorefinery, however, are small because of the very low amount of source separated household food waste.

Figure 5.3 shows all normalized impacts of managing 1000 tons wet Mixed other waste in the four time periods.

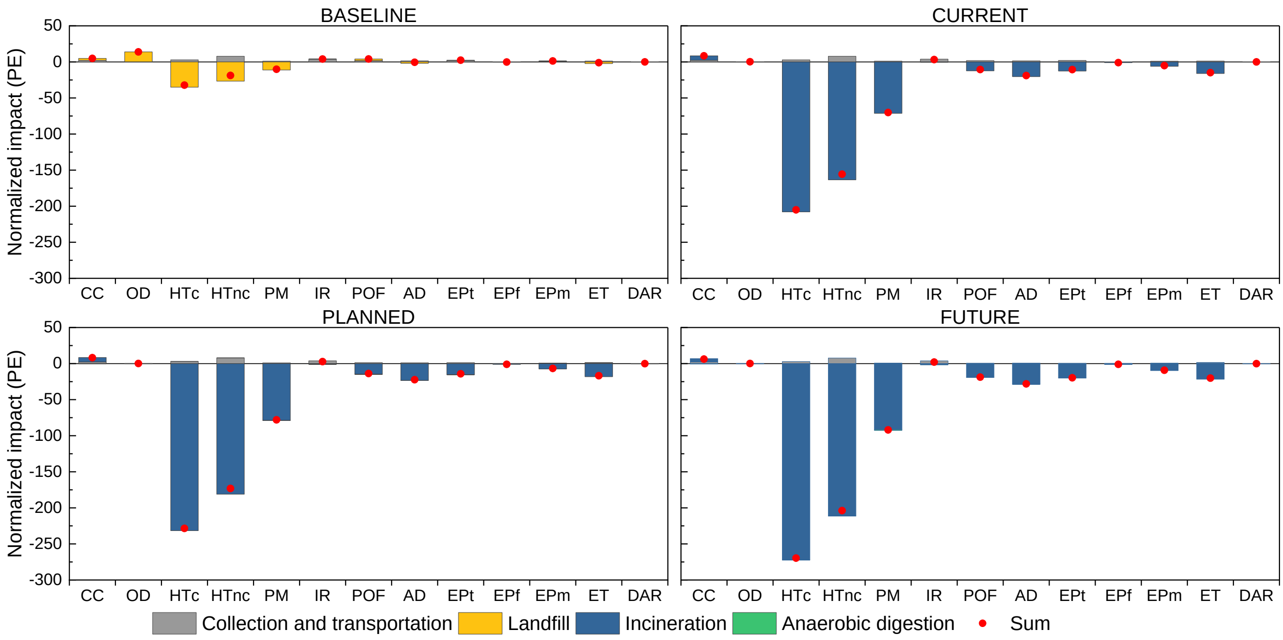


Figure 5.3: Normalized impacts in PE (person-equivalents) per 1000 tons of wet Mixed other waste in four time periods and 13 impact categories: CC- Climate Change, OD – Ozone Depletion, HTc – Human Toxicity (cancer), HTnc – Human Toxicity (non-cancer), PM – Particulate Matter, IR – Ionising Radiation, POF – Photochemical Ozone Formation, AD – Acidification (terrestrial), EPt – Eutrophication (terrestrial), EPf – Eutrophication (freshwater), EPm – Eutrophication (marine), ET – Ecotoxicity (freshwater), DAR – Depletion of abiotic resources, mineral fossil & renewable.

In the BASELINE time period, the normalized impacts show slight savings in some categories, mainly because of energy recovery from landfill gas. Landfill gas emissions contributed to CC and OD significantly due to CH_4 emission. The fuel consumption during transportation also contributes to Photochemical ozone formation (POF), Acidification (AD) and Eutrophication (EP).

In the CURRENT time period, the normalized impacts show significant savings in most categories. This is because incineration avoids significant impacts with respect to Particulate Matter (PM) and Human Toxicity (HT) by substituting electricity mainly from coal power plants; it also benefits with respect to Photochemical ozone formation (POF), Acidification (AD) and Eutrophication (EP). Climate Change (CC) is an exception because of the reasons addressed in Figure 3.5.

In the PLANNED and FUTURE time periods, the impacts in all the categories are slightly improved mainly because of more energy is recovered from incineration with more plastics and less food waste in the Mixed other waste. Anaerobic digestion contributes only slightly to the savings in most categories except for Eutrophication (EP) and Ecotoxicity (ET) due to low amounts of waste treated

5.2 Food waste

Figure 5.4 shows the climate change impacts of managing 1000 tons wet Food waste in the four time periods and Figure 5.5 shows the loads and savings from the individual processes.

In the BASELINE time period, the management of Food waste together with the Mixed other waste in landfill is a significant load to climate change (287 ton/1000 tons). This is mainly due to the landfill gas emissions from the surface of landfill or the leakage of the landfill gas system. In the CURRENT time period, the Food waste was incinerated together with the Mixed other waste, resulting in a net saving to climate change (-112 ton/1000 tons) because of the recovered electricity substituting for the use of fossil fuels for producing electricity. At the same time, the CO_2 emission from incinerating Food waste is biogenic and thus neutral to climate change.

In the PLANNED time period, biorefining of Food waste based on AD is a net saving to climate change though the treated amount is limited by the capacity of the AD palnt (-155 ton/1000 tons). This is mainly due to the energy recovery from biogas generated in AD, as well as the incineration of the solid residues separated from AD. In the FUTURE time period where all the food waste is assumed to be managed with AD, the savings to climate change increases to -229 ton/1000 tons.

Similar to Mixed other waste, transportation of Food waste is also a net load in all scenarios to climate change due to the use of fossil transport fuels and it does not change per 1000 tons of waste over time. In AD, energy recovery from biogas (electricity) avoids significant impacts to climate change. At the same time, incineration of the solid residues from AD also contributes to significant savings due to energy recovery and substitution. Crude oil separated in AD and sold to external use for production of biodiesel also contributes to savings in climate change.

With the increase in AD capacity in progress, the biogas generation and energy recovery in the AD plant increase synchronously, and thus more benefits will be obtained from biogas utilization.

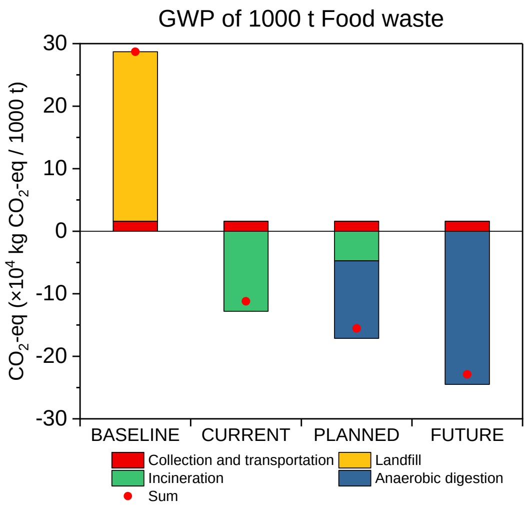


Figure 5.4: Overall climate change impacts as kg CO2-eqv. per 1000 tons of wet Food waste in four time periods

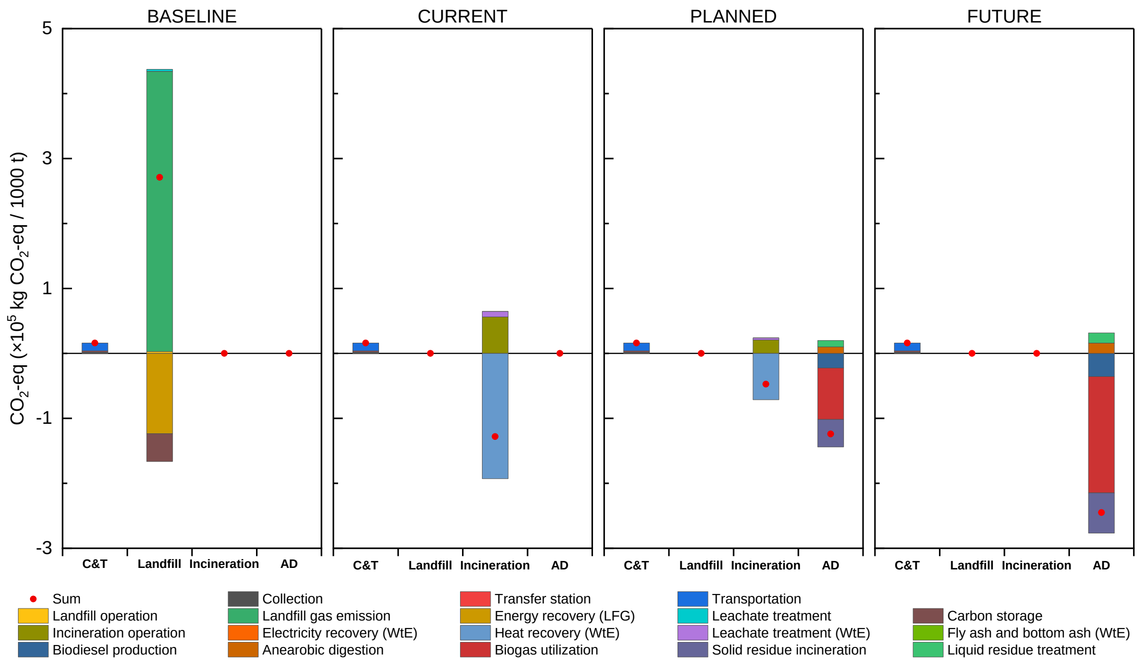


Figure 5.5: Process contribution of climate change impacts as kg CO2-eqv. per 1000 tons of wet Food waste in four time periods

Figure 5.6 shows all normalized impacts of managing 1000 tons wet Food waste in the four time periods.

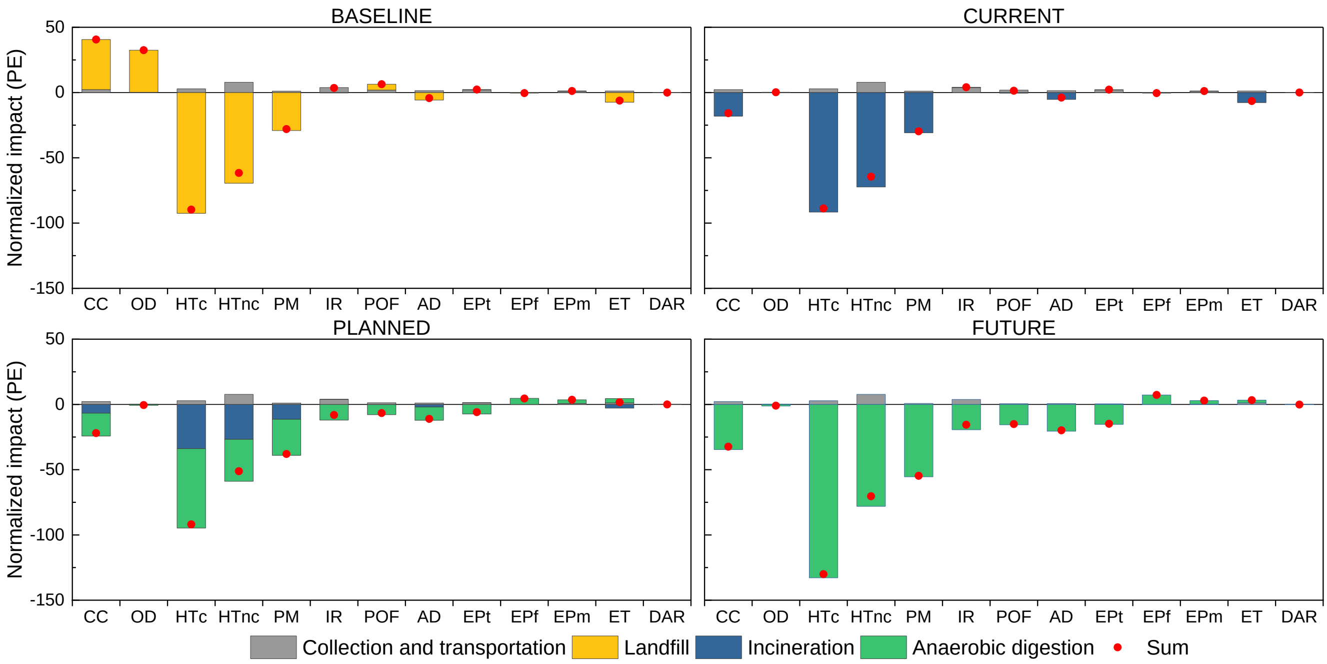


Figure 5.6: Normalized impacts in PE (person-equivalents) per 1000 tons of wet Food waste in four time periods and 13 impact categories: CC- Climate Change, OD – Ozone Depletion, HTc – Human Toxicity (cancer), HTnc – Human Toxicity (non-cancer), PM – Particulate Matter, IR – Ionising Radiation, POF – Photochemical Ozone Formation, AD – Acidification (terrestrial), EPt – Eutrophication (terrestrial), EPf – Eutrophication (freshwater), EPm – Eutrophication (marine), ET – Ecotoxicity (freshwater), DAR – Depletion of abiotic resources, mineral fossil & renewable.

In the BASELINE time period, the normalized impacts show savings in the categories of HTc, HTnc, PM, AD and ET, mainly because of energy recovery from landfill gas. Significant loads to CC and OD is observed, which is mainly attributed to the leakage of landfill gas from the surface.

In the CURRENT time period, the savings to HTc, HTnc, PM, AD and ET are almost the same to those in the BASELINE. This is attributed to the energy recovery from incineration. However, the loads to CC, OD and POF are avoided in the CURRENT time period.

In the PLANNED and FUTURE time periods, the impacts to all the categories are improved except for EPf, EPm and ET, mainly because anaerobic digestion is applied to recover energy from biogas with lower material and energy consumption compared to incineration. The loads to EPf and EPm are mainly from the input specific emission (mainly P and N) in the wastewater treatment after AD. However, these processes are somewhat uncertain because operational data are lacking. The load to ET is mainly derived from enzyme consumption for esterification in biodiesel production; the data of this process are obtained from the literature. Particularly, savings to CC, HT, PM and AD are significantly increased in the FUTURE time period due to electricity recovery from incinerating solid residues. From an environmental perspective, incineration of residues from the AD plant is often more important than biogas generation and utilization in AD because of the background energy system.

5.3 Results for actual amount of waste

The results have so far been presented for 1000 tons of Mixed other waste or1000 tons of Food waste, but Figure 5.7 shows the climate change impacts of managing all the generated Mixed other waste and Food waste in the four time periods.

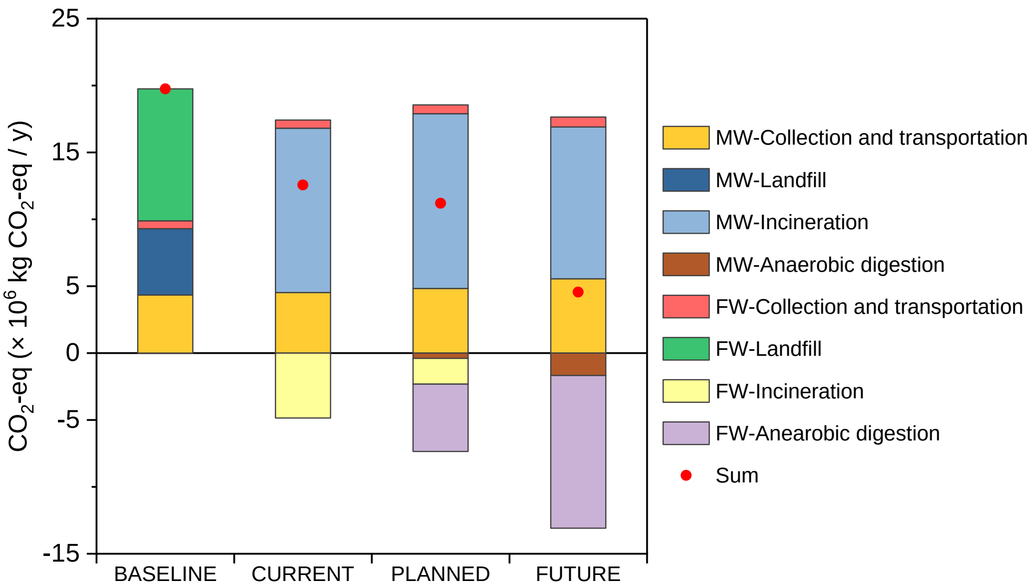


Figure 5.7: Climate change impacts as CO2-eqv. of total amount of Mixed other waste and Food waste in four periods

The overall climate change impact of waste management in Bengbu was in the BASELINE a load of the order of 19 800 tons of CO_2-equivalents per year primarily due to collection and transport and the use of landfilling. In the CURRENT time period the climate change impact has decreased to 12 700 tons of CO_2-equivalents per year. This decrease is due to the incineration of waste (especially Food waste) with an efficient electricity recovery. In contrast, in the PLANNED time period, anaerobic digestion of Food waste and source-separated food waste is in operation, and the overall impact on climate change further decreases to the order of 11 200 tons of CO_2-equivalents per year. However, the load to climate change from the incineration of Mixed other waste increases, because more plastic waste containing fossil carbon and less food waste with biogenic carbon are incinerated. The FUTURE time period suggests that there is further possibilities for improving the waste management system potentially reaching an overall load in climate change of about 4 600 tons of CO_2-equivalents per year. This improvement is primarily due to an increase in the amounts of Food waste handled by AD and improvements in source separation of food waste, as well as in biogas yield from anaerobic digestion and energy recovery from incineration. As seen from Figure 5.7 the climate change impact from collection and transport increases slightly due to the increasing amount of waste suggesting that it may be worth searching for possibilities for reducing the fuel use in collection and transportation. In addition, in all the time periods involving incineration, possibilities for reducing the energy consumption and fossil carbon emissions could also be considered, e.g. facilitating plastic recycling, removing non-combustibles prior to incineration, and carbon capture from the flue gas after incineration.

5.4 Parameter sensitivity analysis

Figure 5.8 shows the sensitivity ratios (SR) of selected input parameters to climate change (CC) impacts in Mixed other waste system during the PLANNED time period. Only the parameters with |SR|>0.05 are listed. Because the CC impacts are positive (58 tons CO_2-eq/1000 ton mixed other waste), positive SRs mean that the increasing parameter values will result in loads to the CC impacts, and negative SRs mean that the increasing parameter values will result in savings. Electricity recovery ratio in incineration is the most sensitive parameter to climate change impacts with an SR of -6.7, indicating that slightly increasing the electricity recovery ratio in incineration can result in significant savings to climate change due to more energy substituted. Two other parameters show |SR|>0.2: electricity consumption in incineration and unit petrol consumption in transportation. These results reveal that using more energy and fuel increases the impacts of the waste management system, therefore saving energy and fuel in waste management is important in order to reduce the climate change impact. At the same time, the more household food waste separated, the more climate change impacts can be avoided. The parameters of gas utilization ratio, electricity recovery ratio and gas yield in AD plant showed negative SRs, suggesting that optimization of the AD operation is also helpful in reducing carbon footprints. However, the parameters in AD plants present very low SRs because only a small amount of waste is routed to AD in the PLANNED time period. It is worth mentioning that, with more food waste separated in the FUTURE time period, the parameters related to AD will become more sensitive.

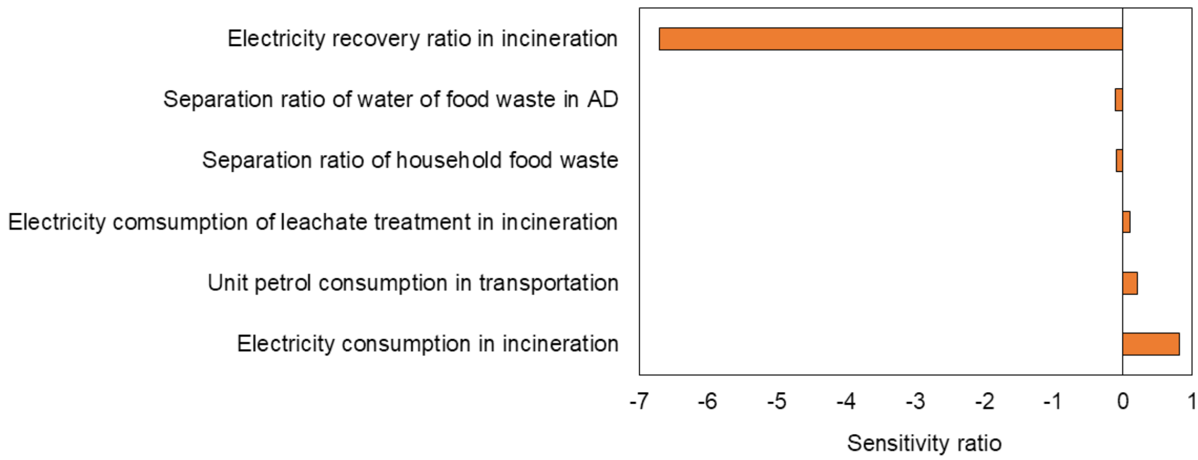


Figure 5.8: Sensitivity ratio (SR) of selected input parameters to Climate change impacts in Mixed other waste system during the PLANNED time period (|SR|>0.05, full list is available in the Appendix)

Figure 5.9 shows the sensitivity ratios (SR) of selected input parameters to climate change impacts in the Food waste management system during the PLANNED time period. Only the parameters with |SR|>0.05 are listed. Since in this scenario the climate change results are a net saving (negative in value, -155 ton CO_2-eq/1000 ton food waste), positive SRs mean that an increasing parameter values will result in savings in the CC impacts, and negative SRs mean that an increasing parameter values will result in loads. The electricity recovery ratio in incineration is also here the most sensitive parameter in CC impacts of the Food waste system with an SR of 0.77, indicating that optimizing the energy recovery in incineration is always beneficial from a climate change perspective. Furthermore, the biogas utilization, energy recovery, solid separation and biogas yield in AD plants are also sensitive parameters, indicating that improving the energy recovery performance in AD plants is important from a climate change perspective. Energy consumptions in incineration, transportation and AD are sensitive parameters with negative SRs, again indicating that saving energy and fuel in waste management is important in order to reduce the climate change impact.

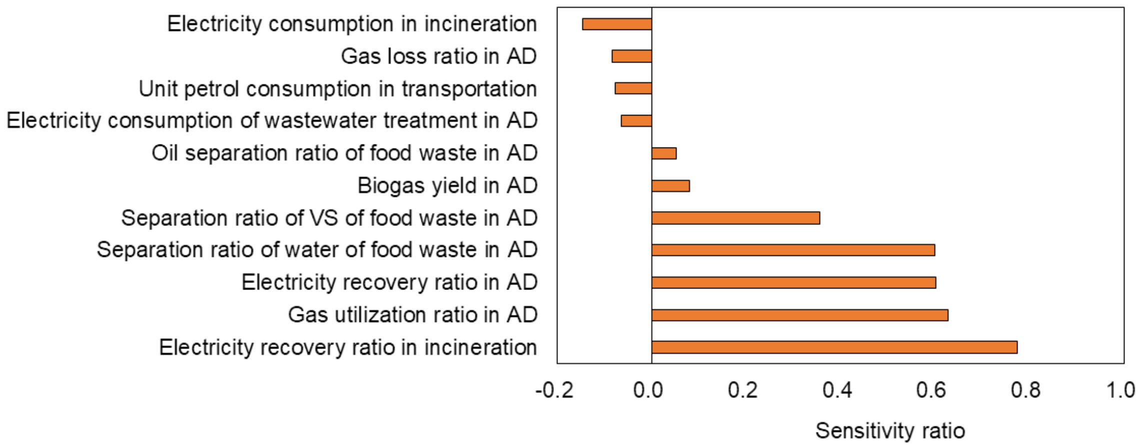


Figure 5.9: Sensitivity ratio (SR) of selected input parameters to Climate change impacts in Food waste system during the PLANNED time period (|SR|>0.05, full list is available in the Appendix)

Also with respect to other environmental impacts, the energy recovery in incineration is the most sensitive parameter in Mixed other waste management in the PLANNED time period. The source separation ratio of household food waste presents considerable SRs to Eutrophication freshwater (-0.12) and Ozone depletion (-0.11). Unit fuel consumptions in collection and transportation also affect Ozone depletion (0.23 and 1.08, respectively), due to the low value of overall impact potential in Ozone depletion (2.06×10^{-6} ton CFC-11-eq/1000 ton mixed other waste). NOx emissions in incineration have SRs of -0.71 and -0.74 in savings in Eutrophication terrestrial and marine, respectively. The SRs of the other parameters in Mixed other waste system are all lower than 0.5 in all the other impact categories. For Food waste system, energy recovery ratio in incineration shows |SR|>0.5 in most impact categories including Human toxicity (cancer and non-cancer effects), Particulate matter, Photochemical ozone formation, Terrestrial acidification, Eutrophication terrestrial, freshwater and marine. Separation ratio of water and VS in AD in progress is also sensitive to Eutrophication terrestrial, freshwater and marine with |SRs| ranging from 0.7 to 4.6. Besides, biogas yield in AD, oil separation in AD, biodiesel production, enzyme consumption in biodiesel production and energy recovery ratios from biogas generated are also important in some of the impact categories including Human toxicity, Ecotoxicity freshwater and Eutrophication Terrestrial. Sensitivity ratios of the PLANNED time period for all impact categories can be found in Appendix.

5.5 Scenario sensitivity analysis

Fig 5.10 shows the climate change impacts of the whole waste system in the FUTURE time period with 16 different scenario assignments as described in Table 4.4. The FUTURE time period is defined as 2025-2035. The results of this scenario sensitivity analysis show that there are further aspects to consider in the continued development in the waste management system in Bengbu.

Increasing the source separation ratio of food waste can provide savings in climate change since more energy can be recovered from AD plants treating food waste (Figure 5.10 A). Source separation of food waste is implemented in Bengbu and the loads to climate change can be reduced by more than half if the source separation ratio can be increased from the 20% assumed in the LCA-modelling to 30%. This may be a moderate source separation ratio for food waste separation in the household, but the results suggest that there are significant benefits in increasing the source separation. This is likely to be due to a combination of less material and energy consumption, more electricity recovered for the grid, more biodiesel production, and an increased heating value of the waste being incinerated. We have not addressed how this assumption fits with available capacities of existing plans.

Recovery of heat in incineration could potentially provide very large additional savings in climate change if the recovered heat is exported to an industrial steam user or used in an external heat or cooling system where fossil-based steam and heat are substituted. Based on the data on the steam produced in the incinerator, around 34% could be recovered as heat as maximum providing additional savings of 57000 ton CO_2-eqvivalents per year by substituting other fossil-based sources

(Figure 5.10 B). However, heat utilization highly depends on the availability of stable and preferably year-round heat consumers, but even utilizing a small proportion of the heat can provide significant benefits in climate change. A significant heat recovery will potentially reduce the net electricity delivery from the incinerator and a specific assessment of the actual plants and their energy-outputs is recommended.

According to a recent study on 23 Danish AD plants, the loss of CH_4 in AD plants ranges from 0.4~14.9% with an average of 4.6%. The value 2.6% of CH_4 loss, which we have used, is an optimistic estimation. However, further improving the AD plants in progress by reducing the fugitive methane loss from 2.6% to 1.5% provide some additional savings of the order of 700 tons CO_2-equivalents per year (Figure 5.10 C). In case the biogas yield from biodegradable carbon is increased from 80% to 85%, which we have used in modelling, the load of the whole system will be further reduced by 22%. This is due to less direct release of CH_4 (CH_4 is 28 times more potent with regard to climate change than CO_2 on a weight basis) and more biogas generation and thus utilization for substituting fossil fuels.

The energy background is extremely important in the climate change impact assessment. In the LCA modelling we have used a fossil-based energy system, which we believe will be the energy technologies affected by the waste system for the years to come. This provides large savings obtained by exporting electricity and fuels to external uses. However, when the background energy becomes greener, the advantages of energy recovery from waste will gradually be reduced and eventually when electricity is fully renewable, the impact from the waste management system will present a significant net load (Figure 5.10 D). If all electricity was supplied by wind power and all heat (which does not contribute in the Bengbu case) was based on biomass the net potential impact on climate change will increase from 4600 tons CO_2-equivalents per year to 148100 tons CO_2-equivalents per year. It is beyond the scope of this study to estimate when the waste management system will exchange with a fully renewable energy system, but it shows that, when considering new investments, maybe expected to have a 30-year lifetime, changes in the background energy system must be addressed. The loads from the waste management system will then in the far future be determined by the fugitive methane losses from AD and the fossil content of the waste incinerated assuming that all collection and transport also are based on electric vehicles. In such a situation, benefits can be obtained potentially from producing storable energy as biodiesel, gas, fuels and eventually heat for local uses.

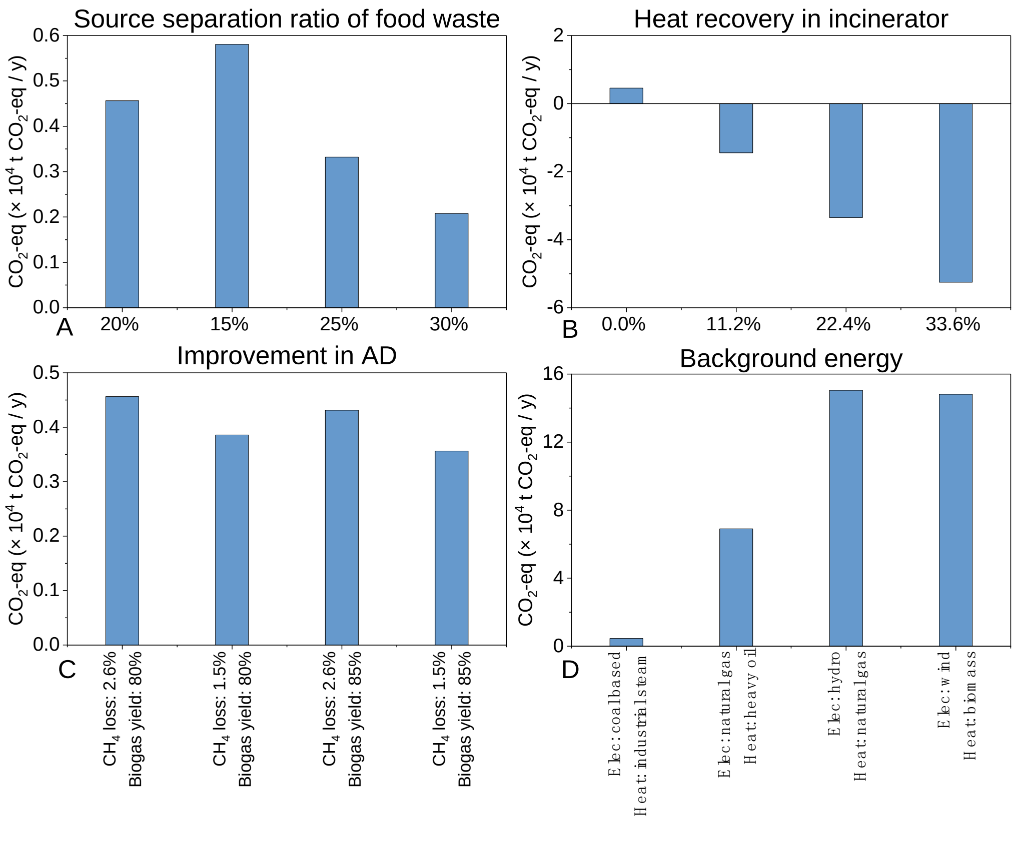


Fig 5.10 Climate Change impacts of the whole waste system in FUTURE time period with scenario variations. Note the variation in Y-axe. The introduced variations are shown in the figure.

5.6 Scenario with central waste sorting

In the additional scenario FUTURE#, a large mechanical sorting facility is included assumed to operate like a large sorting facility in Beijing (Majialou sorting and transfer station). We assume that the mechanical sorting facility involves roller screen, magnetic separation, air separation and manual sorting. The facility can sort the mixed waste into five outputs, including paper, plastic, metal, glass and organic waste. The recyclable outputs are sent for recycling after transportation, and the organic waste and residues are sent for AD and incineration, respectively. The power and water consumptions of operating the sorting facility are 5.44 kWh/t and 114.35 kg/t, respectively, according to the operational data reported by Wang et al. (2013). The transfer coefficients of each fraction to the outputs are provided in Table 4.6. Due to the lack of information, we do not model the cross contamination between different fractions. The recycling processes for paper, plastic, metal and glass are modelled mainly based on Danish and European processes in the database of EASETECH although uncertainty exists about the quality of the recovered products and thus about what they substitute for. The relevant external processes are available in the Appendix.

Fig 5.11 shows the climate change impacts of the whole waste system in the FUTURE# scenario, compared to those in the FUTURE time period. It clearly indicates that scenario FUTURE# avoids significant climate change impacts compared to FUTURE time period. This is mainly due to the recycling of plastic and glass, and the substitution of corresponding material production. At the same time, more food waste is separated and treated with AD, increasing the savings from biogas utilization. In addition, less waste (particularly plastic waste) is incinerated and thus less fossil CO_2 is released from the incinerator; this significantly reduces the overall climate change impacts of the incinerator. The process contribution to climate change impacts in FUTURE# scenario is shown in Fig 5.12. After mechanical sorting, the incineration of the residue is almost neutral in climate change impact, and the plastic recycling is the most important contributor to the significant savings. The latter observations emphasise the need to study the quality of the recovered plastic, because it substitutional value deeply depends on it cleanness in terms of foreign items, polymer type and colour.

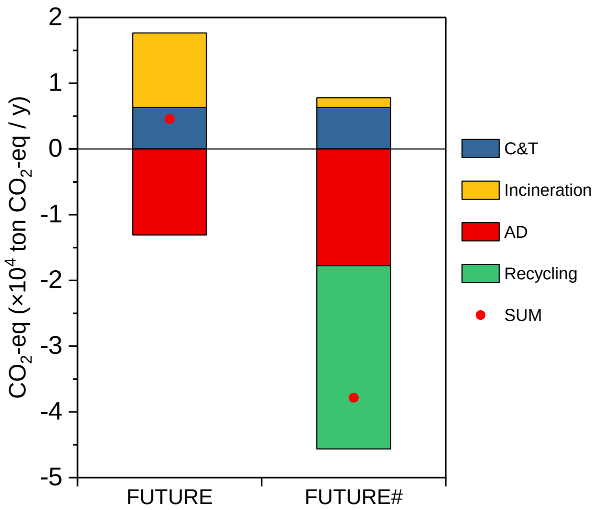


Fig 5.11 Climate Change impacts of the whole waste system in FUTURE# scenario compared with FUTURE time period.

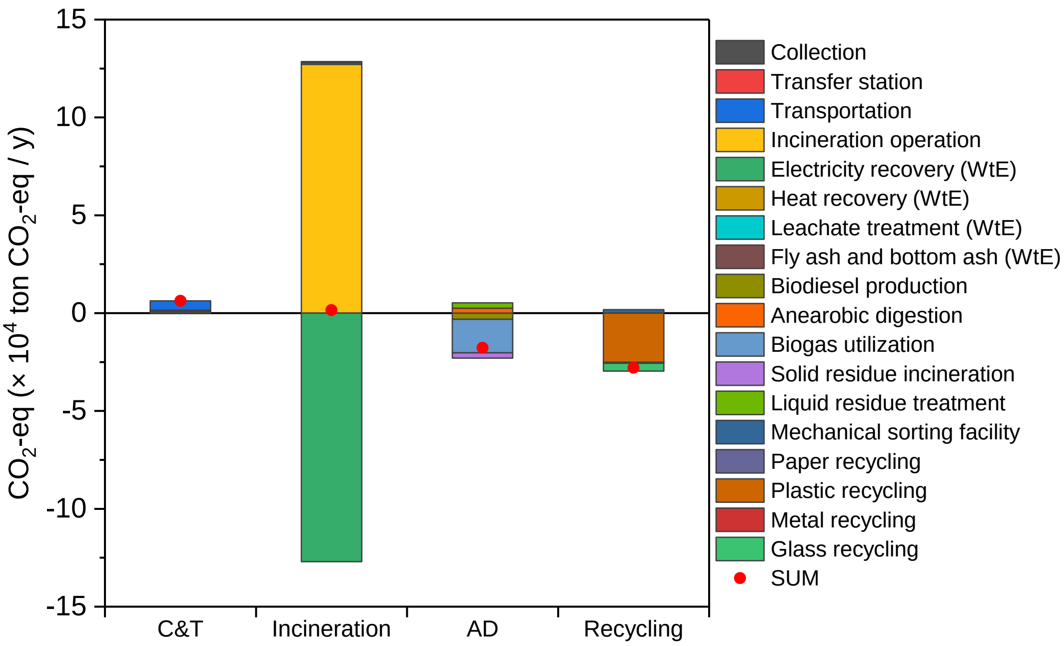


Fig 5.12 Process contribution of climate change impacts as ton CO2-eqv. per year in FUTURE# scenario (C&T: Collection and transport)

6 Conclusions on LCA modelling of the Bengbu waste management system

The first comprehensive life-cycle-assessment of the waste management system in Bengbu has been successfully completed. The modelling includes Mixed other waste from households and Food waste from restaurants and cantinas. Recyclables collected by registered private companies and by the informal sector have not been included due to lack of information about this sector. However, we believe that this sector has considerable positive contributions to waste management and should eventually be considered in any further work on assessing the environmental aspects of waste management in Bengbu.

The LCA modelling covers approximately 1.16 million inhabitants, 283 000 tons Mixed other waste and 37 900 tons Food waste annually (2019).

The modelling builds on a large amount of data from Bengbu making it possible to quantify all significant flows of waste through the waste management system and to model the actual technologies handling the waste. It has been possible to establish flows for four time periods representing important steps in the development of the Bengbu waste management system. The four time periods are: BASELINE 2015-2017, CURRENT 2018-2019, PLANNED 2020-2025 and FUTURE 2025-2035. While the first three periods build on actual data, actual treatment capacities and specific plans, the FUTURE merely presents potential further improvements that could be considered, although no plans address activities after 2025. In spite of some data gaps and some minor inconsistencies in the collected data, we trust that the flows established represent well the actual flows of waste throughout the systems. The main uncertainties lay with the residues from the treatment facilities, but we do not expect this to affect the overall results in general. Regarding the waste compositions and the waste technologies, it has been necessary in some case to supplement the local data with other Chinese data and in some case also data from the general literature. However, we suggest that in future mapping of the waste management in Bengbu more emphasis be put on measuring and controlling the water content of the waste fractions and determining of the content of fossil and biogenic carbon in the waste. The first is related to the fact that all field measurements and modelled flows use wet weight data, but the mass conservation and conversion in the handling processes address the solids. Thus, water content becomes important in order to keep account of the masses. The second aspects is due to the fact that greenhouse gas emissions are counted differently for fossil and biogenic carbon, and the emission of fossil based carbon dioxide is a direct load to climate change and thus important to precisely quantify. In the modelling, European data has been used regarding the fossil and biogenic carbon in the waste fractions. It should also be mentioned that we, because of lack of data, assumed that the food waste separated at source in the households contained no foreign items or impurities. This is probably of little importance in the current modelling, because the flow is small, but if this flow becomes larger in the future, the amount of foreign items that needs to be removed must be quantified.

The modelling was done separately for 1000 ton of each of the two waste types in order to focus on how handling of the waste as well as type and operation of technologies employed affected the environmental impacts. However, the result are proportional with the amount of waste handled and results have also been provided for the total amount of waste within each time period. Although the CURRENT time period covering two years in fact is a transition period involving closing of landfills and establishing efficient incineration and anaerobic digestion, we did not specifically address the transition between the periods and assumed conditions and data constant within each period.

The LCA results clearly show that the development of the Bengbu waste management system from 2015 to 2025 as represented by the BASELINE, the CURRENT and the PLANNED time periods leads to significant environmental improvements. Using climate change impact as the main indicator, the BASELINE time period showed a load in terms of climate change of about 19800 tons CO_2 equivalents per year while the PLANNED time period shows a load of only 11200 tons CO_2 equivalents per year, corresponding to an improvement of the order of 8600 tons CO_2 equivalents per year. The improvement is however only of the order of 7 kg CO_2 equivalents per citizen and year.

All other environmental impacts considered also show improvement from the BASELINE to the CURRENT time period. Some of these impacts are actual savings.

The LCA clearly shows that ceasing landfilling provided environmental benefits, and that introduction of anaerobic digestion and incineration with energy recovery has provided environmental benefits in the PLANNED time period. It is also clearly documented that collection and transport of the waste using fossil-fuel based vehicles is a large contribution to climate change impacts. It is worth noting that nearly all benefits come from the recovery of energy, primarily electricity from the incinerator, but also energy as electricity and biodiesel from the anaerobic digestion; the latter is primarily observed in the PLANNED and FUTURE time periods. The benefit is from substituting traditional fossil energy sources. The electricity recovery of the incinerator is by far the most important single parameter in controlling the climate change impacts from the waste management system. It is the net export of electricity from the incinerator that matters, thus also the internal electricity use at the incinerator is of importance: the lower the internal electricity use, the higher the export and thus the credits obtained from substituting fossil-based electricity. In terms of optimizing technology parameters, the results suggest to focus on:

- Increase electricity recovery at incinerator
- Improve source separation of food waste in households
- Decrease electricity use in incinerator
- Decrease electricity use in treatment of bunker leachate
- Reduce petrol consumption in collection and transport of waste
- Increase gas production in anaerobic digestion
- Decrease electricity use in treating wastewater from anaerobic digestion
- Prevent biogas loss in AD plants

The LCA results clearly show that introduction of heat recovery at the incinerator assuming there is an external market for the heat, would have potential for great additional savings in climate change impacts. If significant heat was recovered and substituted for fossil-based heat, it could provide net savings in climate change by a factor of ten. It is beyond the scope of this project to assess the feasibility of exporting heat from incineration in Bengbu, but the analysis suggests a large potential that could be considered after a close market analysis.

The LCA results show as well that an increase in source separation of household food waste, full capacity for anaerobic digestion of the food waste and prevention of biogas loss could provide savings in climate change. At the same time the separated solids become drier and the digestate is also suitable for incineration with energy recovery after solid-liquid separation. Optimization of the anaerobic digestion, limitation of fugitive methane losses as well as the liquid residue treatment must be carefully considered to obtain the maximum of benefits.

A crucial factor controlling the environmental aspects of the Bengbu waste management system is the benefits coming from energy substitution. The modelling assumes substitution of fossil-based energy, but the energy system in China will undergo large changes during the next decades in the quest for a more renewable energy system. If the recovered energy in the future no longer substitutes for fossil-based energy source, the savings will be less and the loads to climate change impact will increase correspondingly. This also means that the technologies to focus on and to optimize will change. It is beyond the scope of this study to identify which energy technologies the waste management system will interact with in the future and when eventual changes will take place. However, we do not expect to see major changes within the next 10 years, but in the future storable energy and fuels may have more value than electricity and heat and it may become of more importance to reduce the direct emission of greenhouse gases from the waste management system.

In addition, a large mechanical sorting facility is under consideration in Bengbu. LCA results indicate that mechanical sorting of the Mixed other waste can avoid significant climate change impacts by waste recycling and substituting corresponding raw materials including plastics and glass, and at the same time reducing fossil carbon emissions from incineration of plastic. Mechanical sorting also increase food waste separation and increases the savings from biogas utilization in AD. A large mechanical sorting facility is thus considered beneficial from an environmental impact perspective. However, the quality of the sorted materials is crucial for obtaining the estimated credits from substituting the production of virgin materials. We suggest that these aspects be further assessed before any decision is made regarding the establishment of a central sorting facility. . In addition, sorting and landfilling of inert factions not suitable for incineration should also be considered, since the incinerator today receives significant amounts of non-combustible waste as part of the Mixed other waste.

We suggest that LCA-modelling becomes integrated into the waste management of Bengbu as part of the reporting of the environmental aspects of the implementation of current plans (by updating the LCA modelling for example every three years to document progress) and as a quantitative tool in assessing new initiative as part of the planning process so new investments can provide significant environmental improvements.

A Appendix – LCA documentation

List of Content

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