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SUPPORTING MATERIAL A
System boundaries and life cycle inventory

Article: "An environmental and economic assessment of bioplastic from urban biowaste: The example of polyhydroxyalkanoate (PHA)"

Susanna Andreasi Bassi[1], Alessio Boldrin[1], Giammarco Frenna[2], Thomas F. Astrup[1]*

*) Corresponding author: Susanna Andreasi Bassi, suan@env.dtu.dk

[1] Department of Environmental Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark

[2] Department of Environmental Sciences, Informatics and Statistics, Ca' Foscari University of Venice, IT-30172 Mestre (VE), Italy

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1 Abbreviation

AN	Ammonium nitrate;
AS	Ammonium sulfate;
AD	Anaerobic digestion
BMP	Biochemical Methane Potential
CAPEX	capital expenditures
CHP	Combined heat and power
DAP	Diammonium phosphate;
LCA	Life cycle assessment
LCC	Life cycle costing
LHV	Low heating value
LDPE	Low-density polyethylene
MBP	Mechanical biological pre-treatment
MBS	Mechanical biological stabilization
MBT	Mechanical biological treatment;
MAP	Monoammonium phosphate;
FW	Municipal food waste
PM	Particular matter
PHA	Polyhydroxyalkanoates
PUR	Polyurethane
SS	Sewage sludge
SSP	Single superphosphates
TSP	Triple superphosphate;
UAN	Urea ammonium nitrate;
UOL	Use-on-land;
VS	Volatile solid
WWTP	Wastewater treatment plant

2 System boundaries

In this section the system boundaries of each alternative scenario in each cluster is clarified.

2.1 System boundaries of the counter factuals

2.1.1 Barcelona

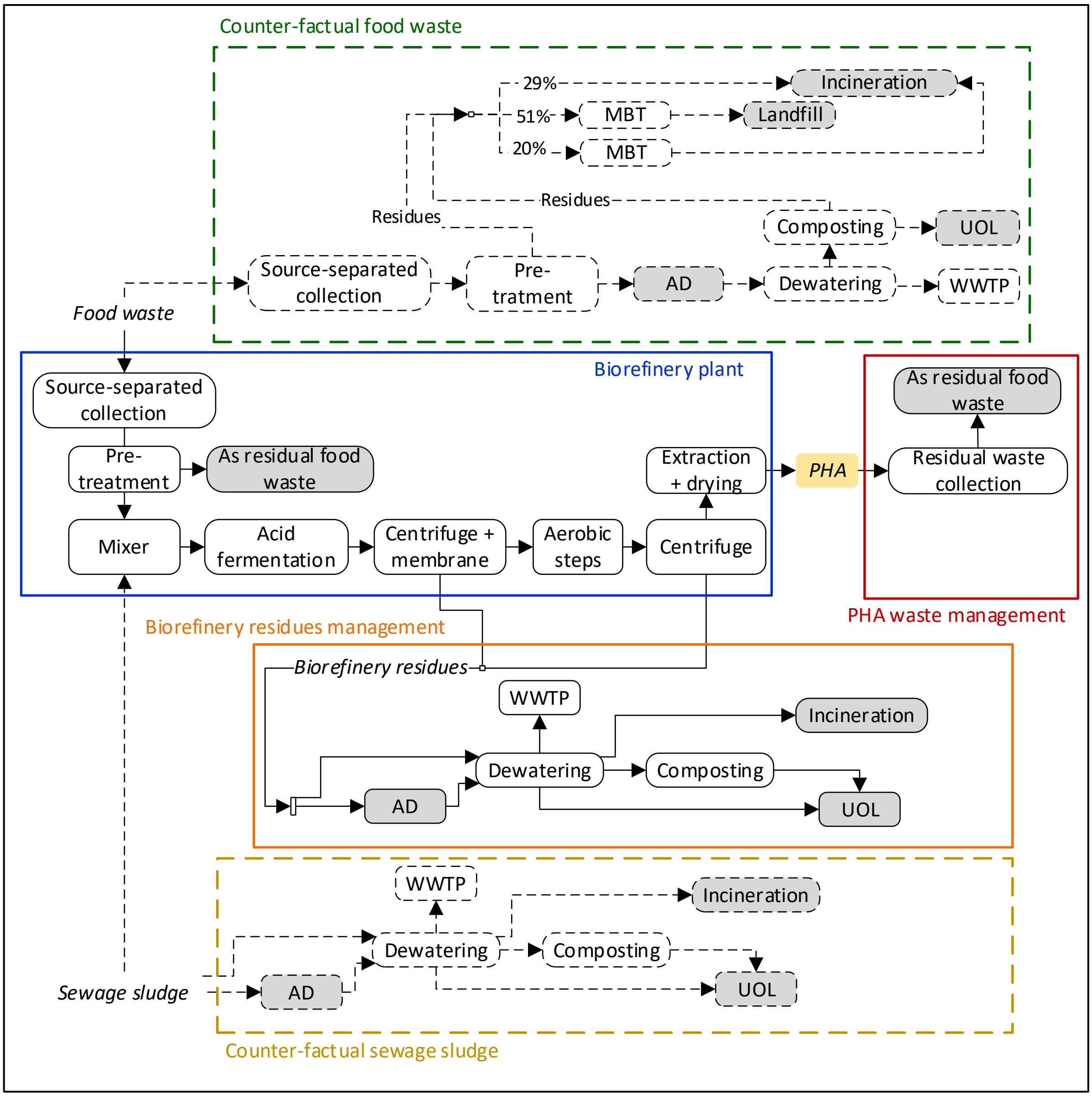

Figure 1: System boundaries of the alternative scenario "FW_sep." for Barcelona. The PHA production process was divided into the plant itself (in blue), the treatment of the biorefinery residues (in orange), and the incineration/landfilling of the PHA (in red). The dotted lines indicate the food waste counter-factual (in green) and sewage sludge counter-factual (in yellow), which are modeled by subtracting them from the PHA production process. The treatment of the biorefinery residues is always equal to the sewage sludge counter-factual. Filled processes indicate by-products (energy or fertilizers) that avoid the production of marginal energy or marginal mineral fertilizers. MBT: mechanical biological treatment; UOL: use-on-land; WWTP: wastewater treatment plant; AD: anaerobic digestion

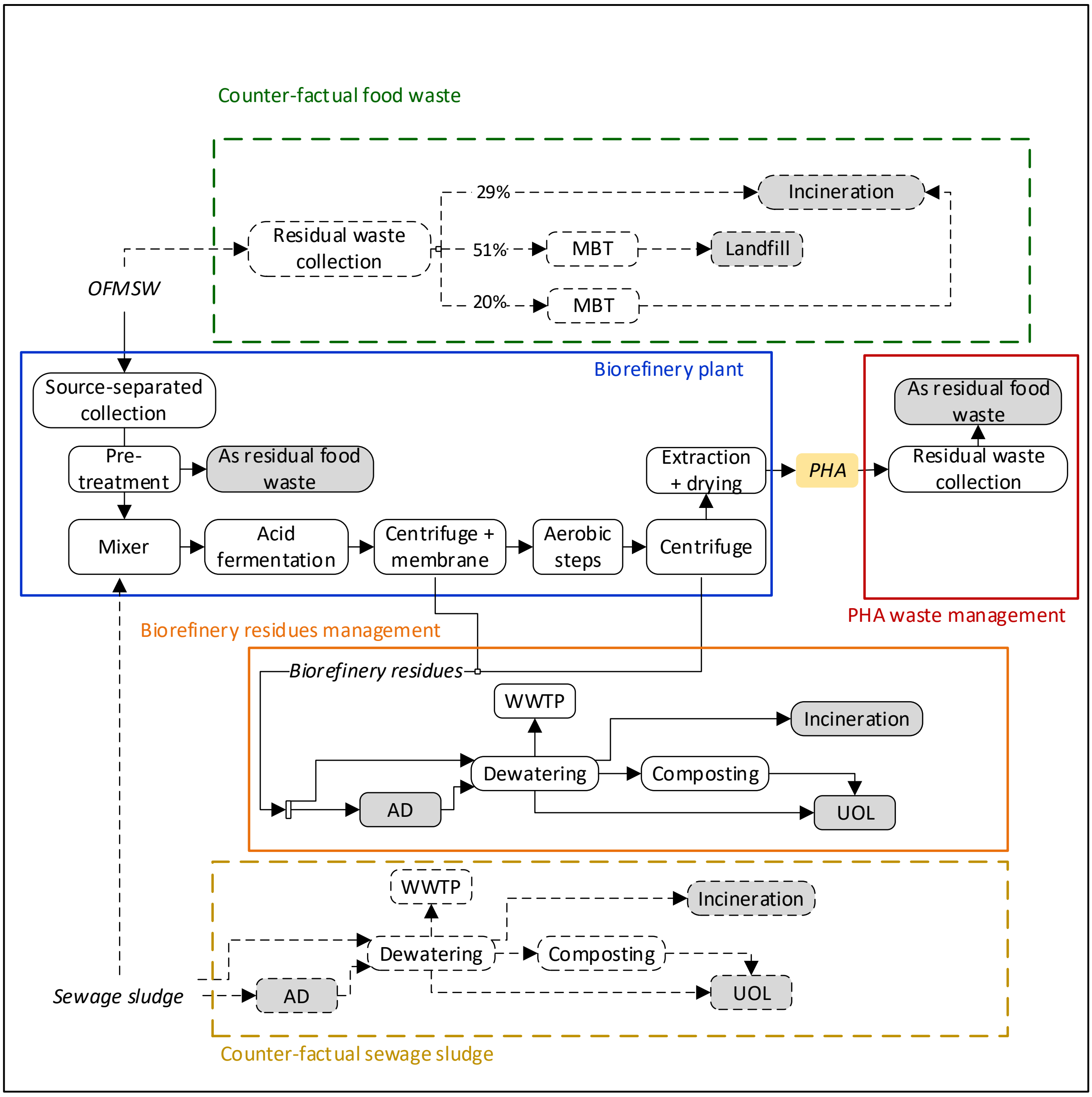

Figure 2: System boundaries of the alternative scenario "FW_residual." for Barcelona. The PHA production process was divided into the plant itself (in blue), the treatment of the biorefinery residues (in orange), and the incineration/landfilling of the PHA (in red). The dotted lines indicate the food waste counter-factual (in green) and sewage sludge counter-factual (in yellow), which are modeled by subtracting them from the PHA production process. The treatment of the biorefinery residues is always equal to the sewage sludge counter-factual. Filled processes indicate by-products (energy or fertilizers) that avoid the production of marginal energy or marginal mineral fertilizers. MBT: mechanical biological treatment; UOL: use-on-land; WWTP: wastewater treatment plant; AD: anaerobic digestion.

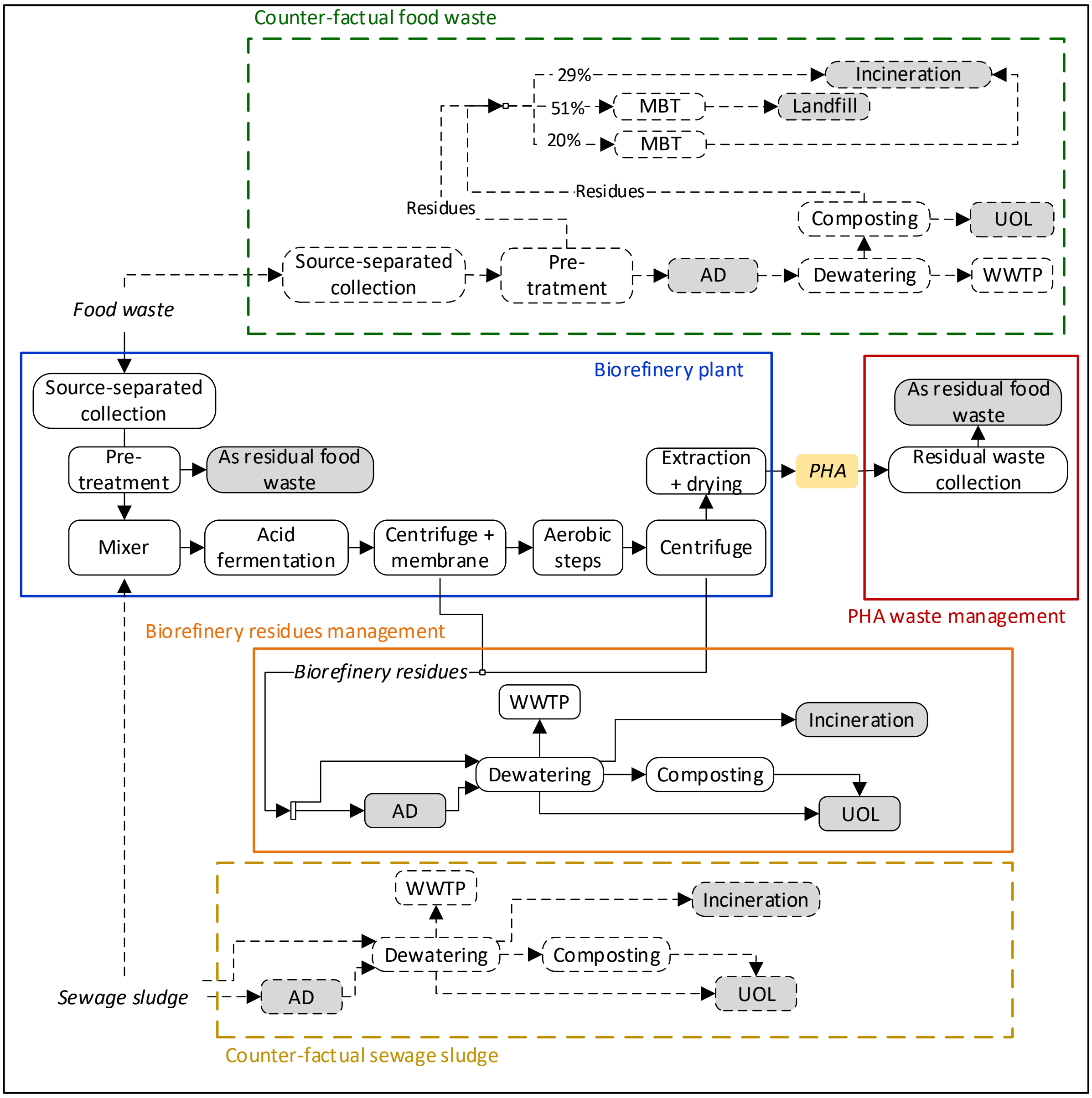

Figure 3: System boundaries of the alternative scenario "FW_AD." for Barcelona. The PHA production process was divided into the plant itself (in blue), the treatment of the biorefinery residues (in orange), and the incineration/landfilling of the PHA (in red). The dotted lines indicate the food waste counter-factual (in green) and sewage sludge counter-factual (in yellow), which are modeled by subtracting them from the PHA production process. The treatment of the biorefinery residues is always equal to the sewage sludge counter-factual. Filled processes indicate by-products (energy or fertilizers) that avoid the production of marginal energy or marginal mineral fertilizers. MBT: mechanical biological treatment; UOL: use-on-land; WWTP: wastewater treatment plant; AD: anaerobic digestion

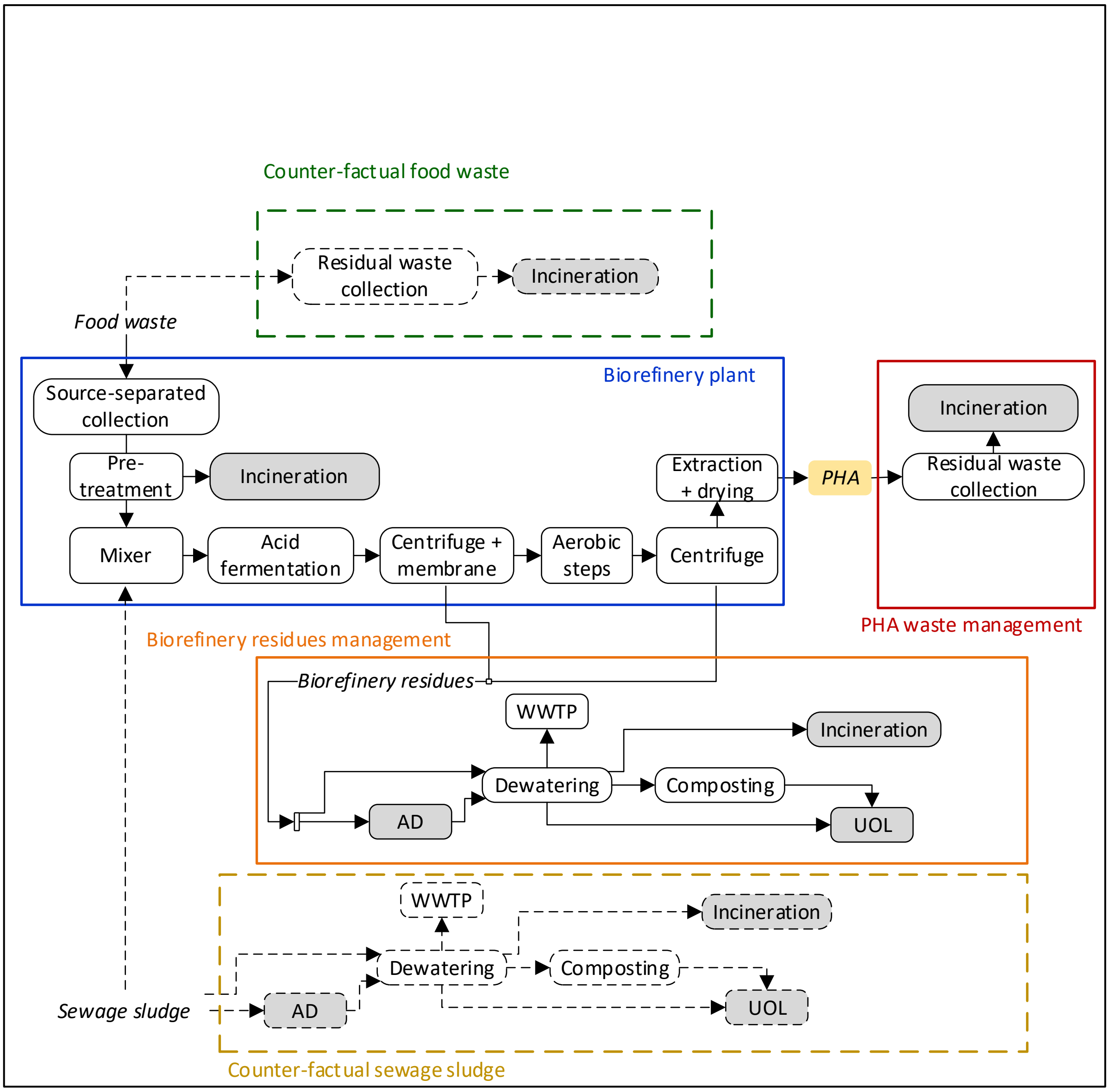

Figure 4: System boundaries of the alternative scenario "FW_Incl." for Barcelona. The PHA production process was divided into the plant itself (in blue), the treatment of the biorefinery residues (in orange), and the incineration/landfilling of the PHA (in red). The dotted lines indicate the food waste counter-factual (in green) and sewage sludge counter-factual (in yellow), which are modeled by subtracting them from the PHA production process. The treatment of the biorefinery residues is always equal to the sewage sludge counter-factual. Filled processes indicate by-products (energy or fertilizers) that avoid the production of marginal energy or marginal mineral fertilizers. MBT: mechanical biological treatment; UOL: use-on-land; WWTP: wastewater treatment plant; AD: anaerobic digestion

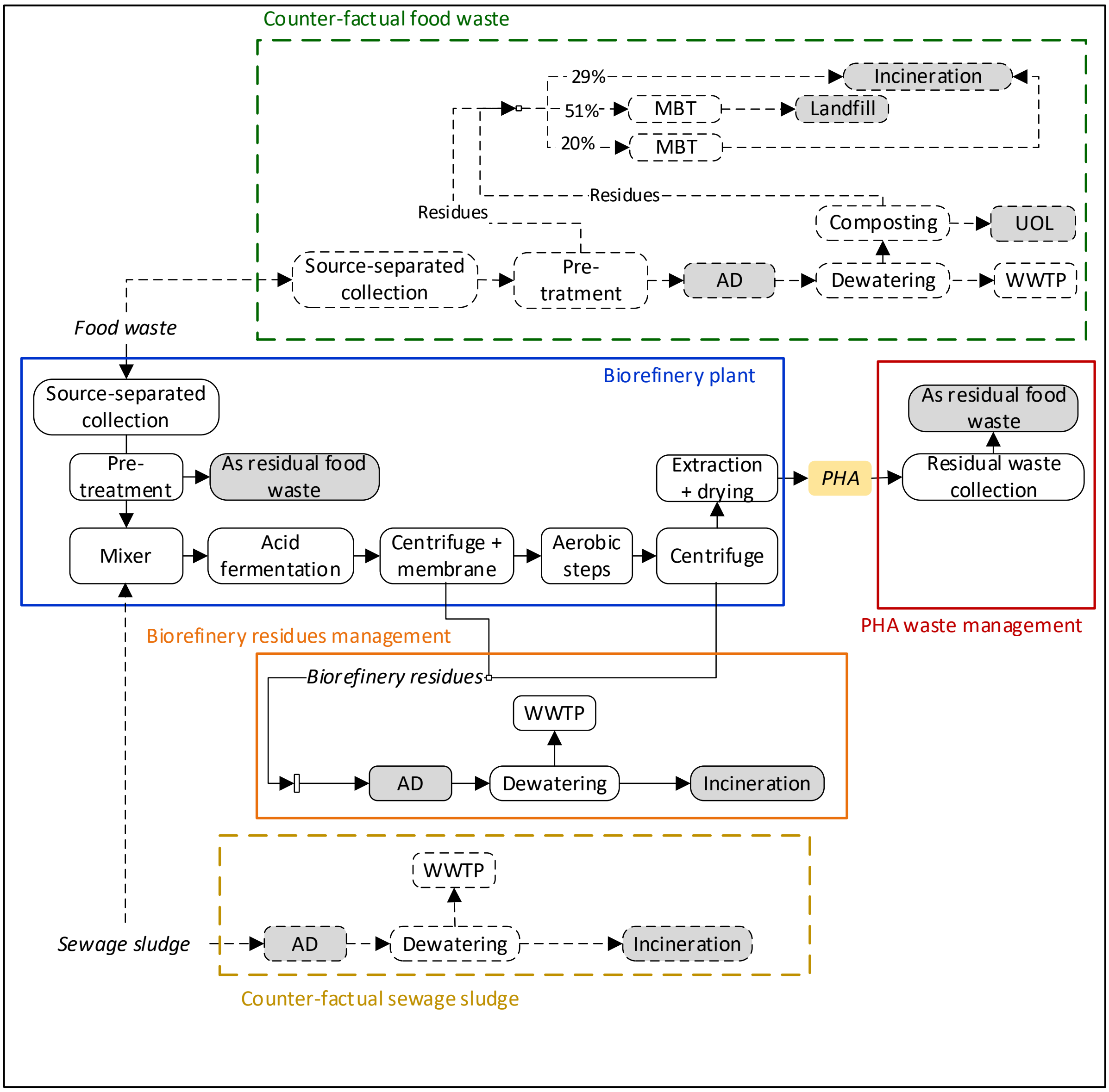

Figure 5: System boundaries of the alternative scenario "SS_AD_Inc." for Barcelona. The PHA production process was divided into the plant itself (in blue), the treatment of the biorefinery residues (in orange), and the incineration/landfilling of the PHA (in red). The dotted lines indicate the food waste counter-factual (in green) and sewage sludge counter-factual (in yellow), which are modeled by subtracting them from the PHA production process. The treatment of the biorefinery residues is always equal to the sewage sludge counter-factual. Filled processes indicate by-products (energy or fertilizers) that avoid the production of marginal energy or marginal mineral fertilizers. MBT: mechanical biological treatment; UOL: use-on-land; WWTP: wastewater treatment plant; AD: anaerobic digestion

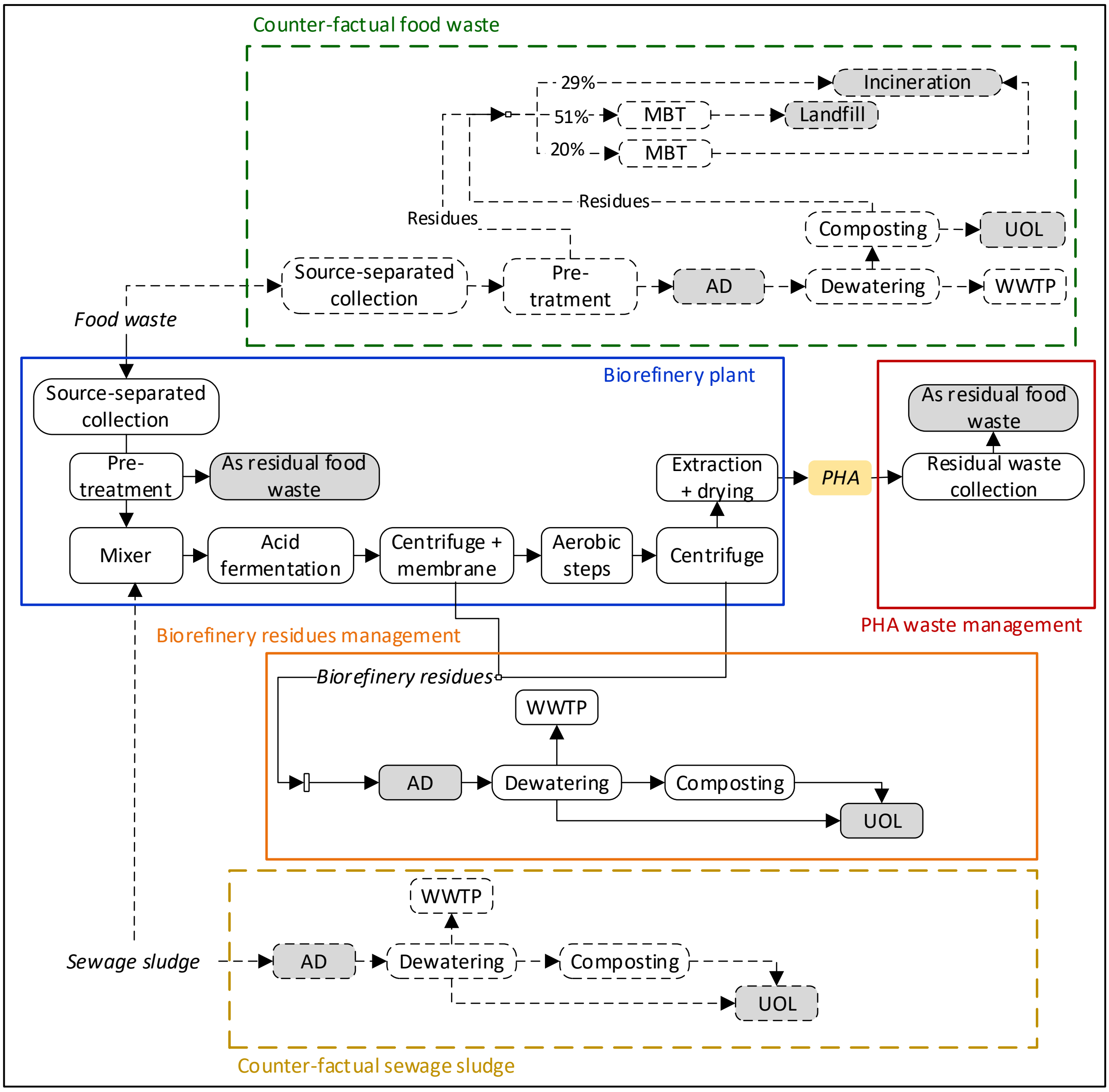

Figure 6: System boundaries of the alternative scenario "SS_AD_UOL" for Barcelona. The PHA production process was divided into the plant itself (in blue), the treatment of the biorefinery residues (in orange), and the incineration/landfilling of the PHA (in red). The dotted lines indicate the food waste counter-factual (in green) and sewage sludge counter-factual (in yellow), which are modeled by subtracting them from the PHA production process. The treatment of the biorefinery residues is always equal to the sewage sludge counter-factual. Filled processes indicate by-products (energy or fertilizers) that avoid the production of marginal energy or marginal mineral fertilizers. MBT: mechanical biological treatment; UOL: use-on-land; WWTP: wastewater treatment plant; AD: anaerobic digestion

2.1.2 Copenhagen

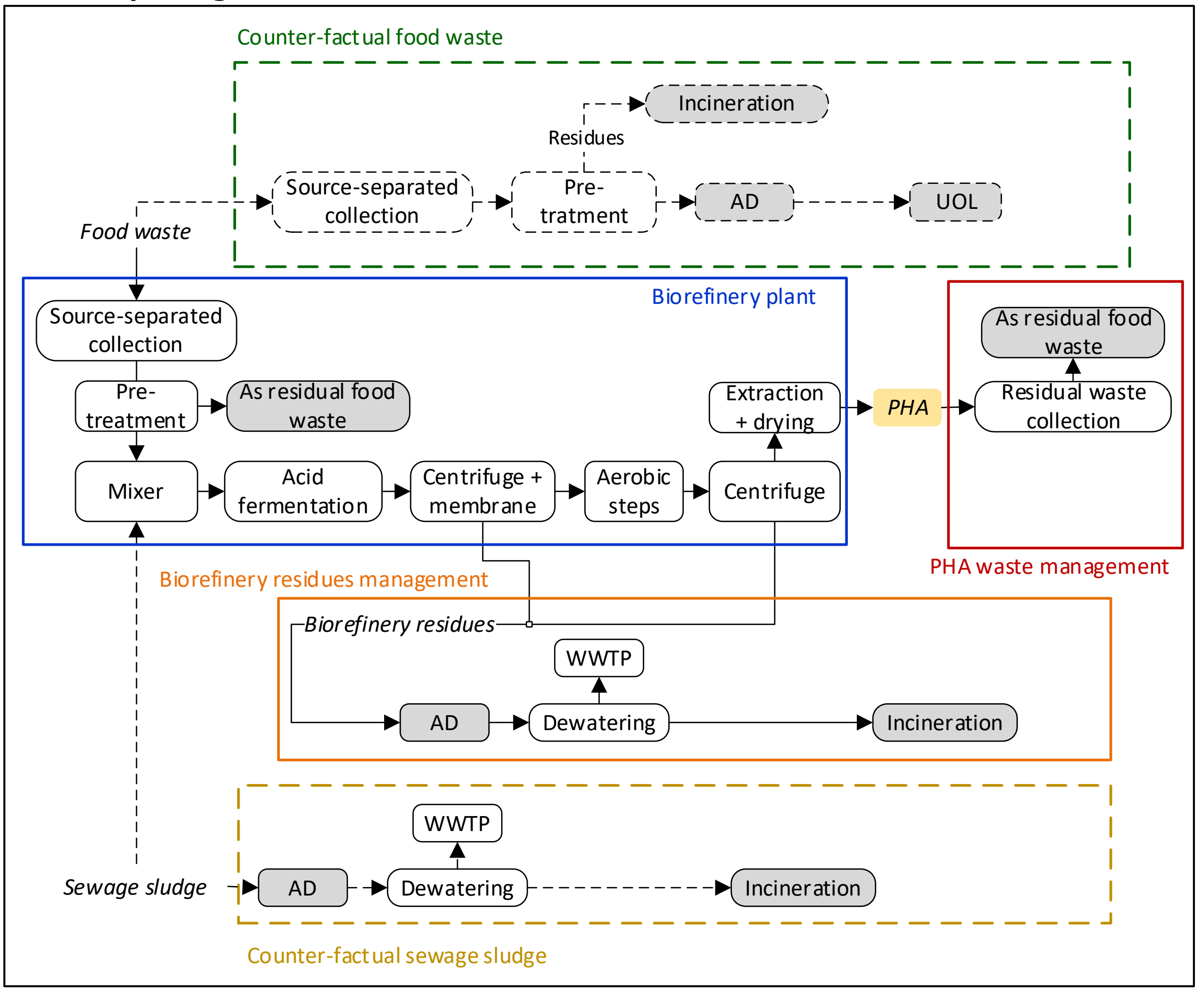

Figure 7: System boundaries of the alternative scenario "FW_sep." for Copenhagen. The PHA production process was divided into the plant itself (in blue), the treatment of the biorefinery residues (in orange), and the incineration/landfilling of the PHA (in red). The dotted lines indicate the food waste counter-factual (in green) and sewage sludge counter-factual (in yellow), which are modeled by subtracting them from the PHA production process. The treatment of the biorefinery residues is always equal to the sewage sludge counter-factual. Filled processes indicate by-products (energy or fertilizers) that avoid the production of marginal energy or marginal mineral fertilizers. MBT: mechanical biological treatment; UOL: use-on-land; WWTP: wastewater treatment plant; AD: anaerobic digestion

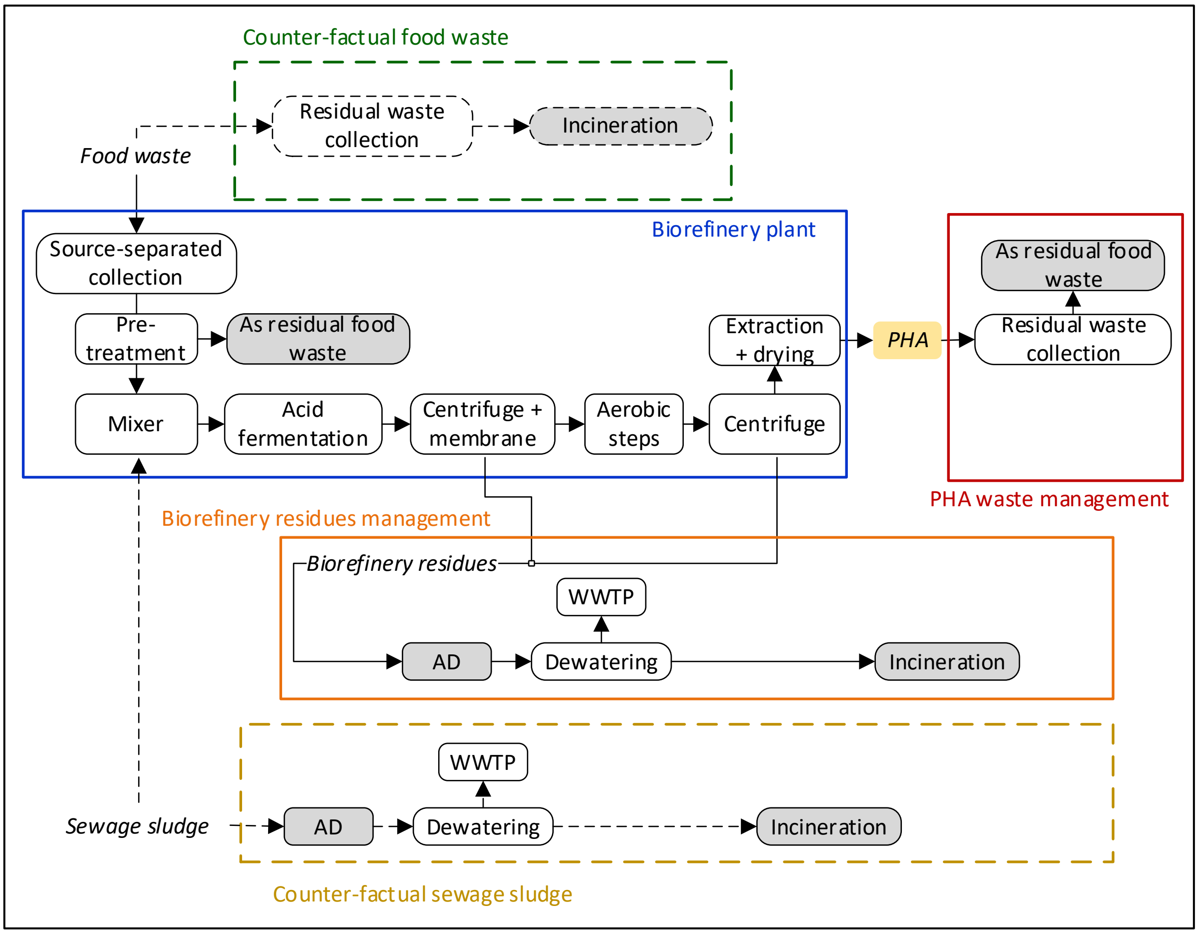

Figure 8: System boundaries of the alternative scenario "FW_residual." for Copenhagen. The PHA production process was divided into the plant itself (in blue), the treatment of the biorefinery residues (in orange), and the incineration/landfilling of the PHA (in red). The dotted lines indicate the food waste counter-factual (in green) and sewage sludge counter-factual (in yellow), which are modeled by subtracting them from the PHA production process. The treatment of the biorefinery residues is always equal to the sewage sludge counter-factual. Filled processes indicate by-products (energy or fertilizers) that avoid the production of marginal energy or marginal mineral fertilizers. MBT: mechanical biological treatment; UOL: use-on-land; WWTP: wastewater treatment plant; AD: anaerobic digestion.

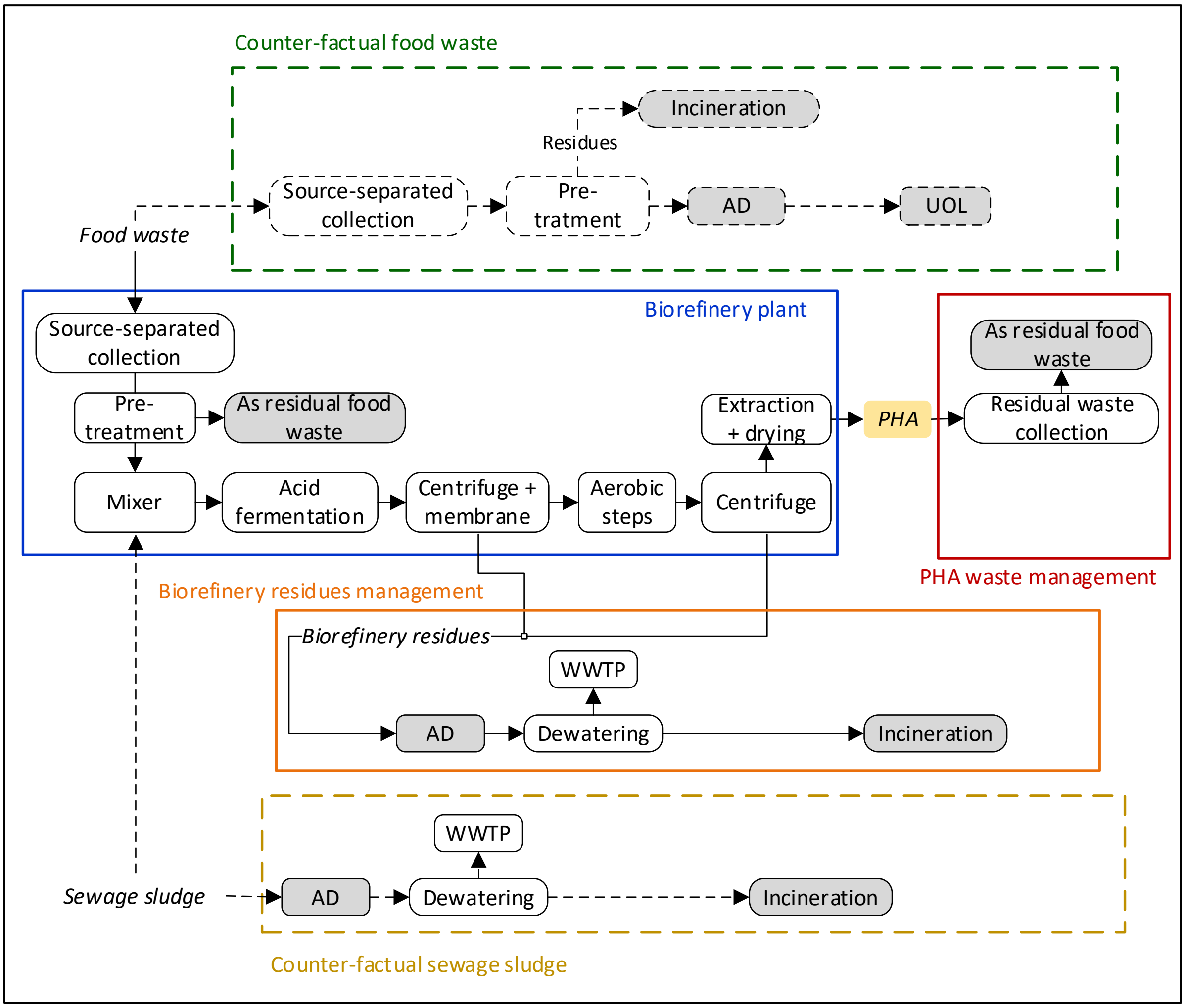

Figure 9: System boundaries of the alternative scenario "FW_AD." for Copenhagen. The PHA production process was divided into the plant itself (in blue), the treatment of the biorefinery residues (in orange), and the incineration/landfilling of the PHA (in red). The dotted lines indicate the food waste counter-factual (in green) and sewage sludge counter-factual (in yellow), which are modeled by subtracting them from the PHA production process. The treatment of the biorefinery residues is always equal to the sewage sludge counter-factual. Filled processes indicate by-products (energy or fertilizers) that avoid the production of marginal energy or marginal mineral fertilizers. MBT: mechanical biological treatment; UOL: use-on-land; WWTP: wastewater treatment plant; AD: anaerobic digestion

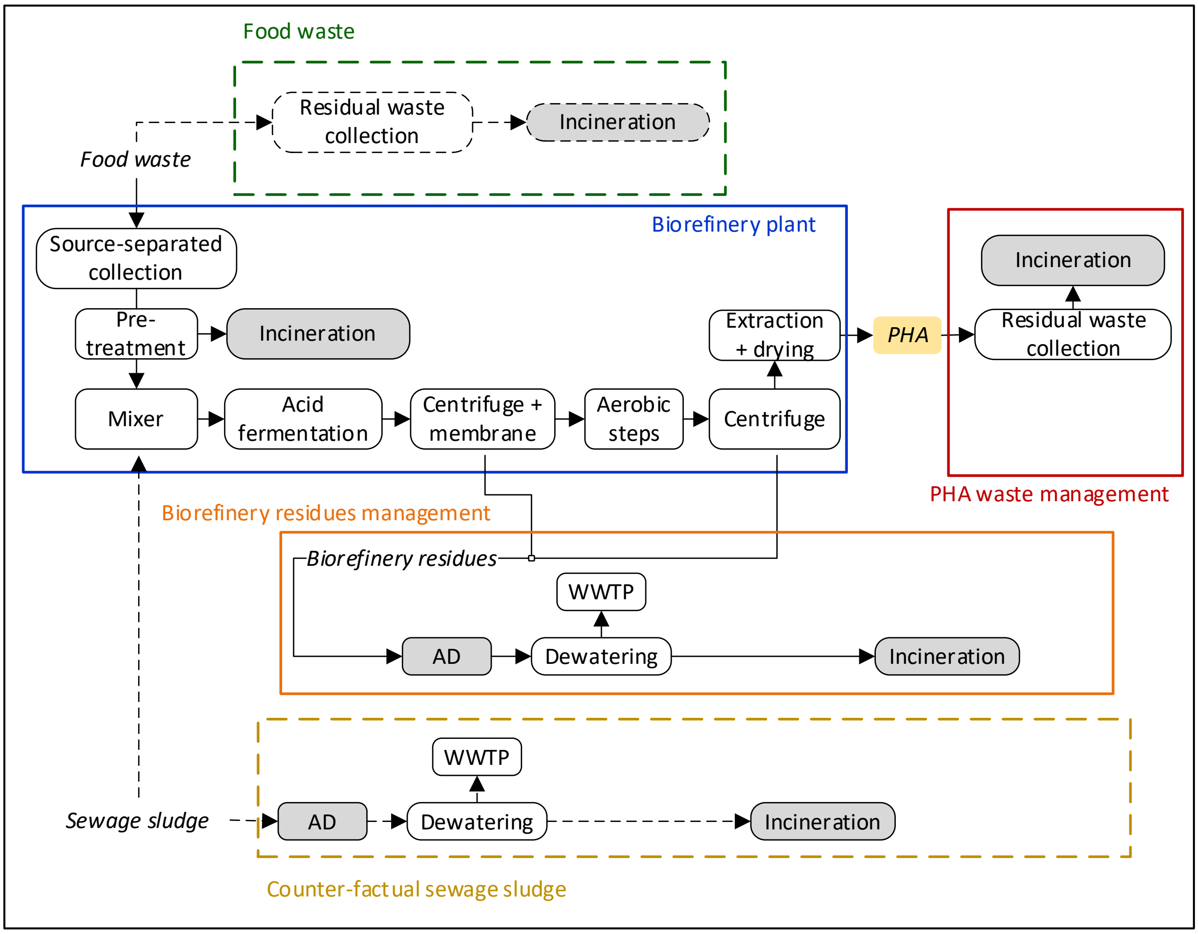

Figure 10: System boundaries of the alternative scenario "FW_Incl." for Copenhagen. The PHA production process was divided into the plant itself (in blue), the treatment of the biorefinery residues (in orange), and the incineration/landfilling of the PHA (in red). The dotted lines indicate the food waste counter-factual (in green) and sewage sludge counter-factual (in yellow), which are modeled by subtracting them from the PHA production process. The treatment of the biorefinery residues is always equal to the sewage sludge counter-factual. Filled processes indicate by-products (energy or fertilizers) that avoid the production of marginal energy or marginal mineral fertilizers. MBT: mechanical biological treatment; UOL: use-on-land; WWTP: wastewater treatment plant; AD: anaerobic digestion

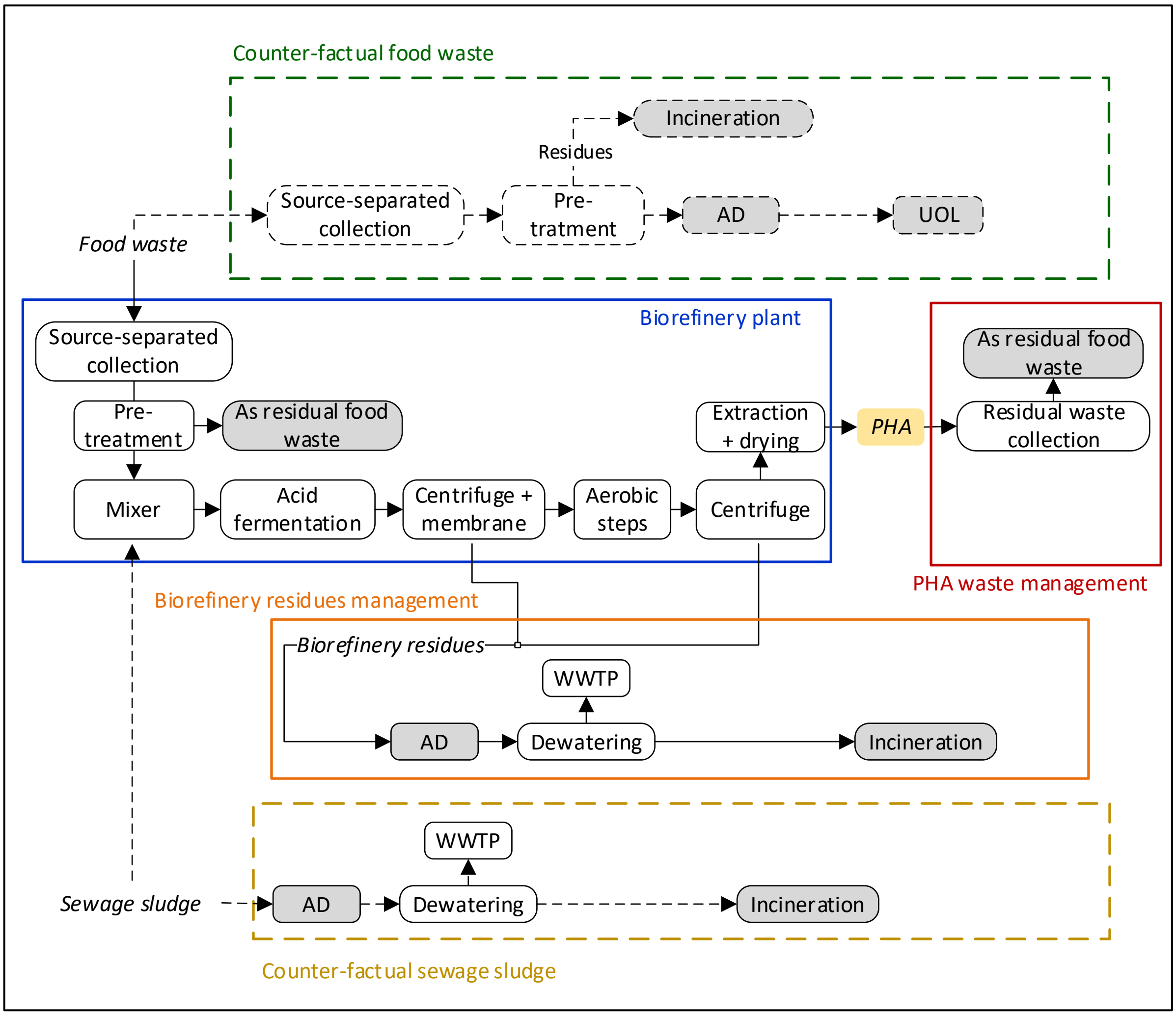

Figure 11: System boundaries of the alternative scenario "SS_AD_Inc." for Copenhagen. The PHA production process was divided into the plant itself (in blue), the treatment of the biorefinery residues (in orange), and the incineration/landfilling of the PHA (in red). The dotted lines indicate the food waste counter-factual (in green) and sewage sludge counter-factual (in yellow), which are modeled by subtracting them from the PHA production process. The treatment of the biorefinery residues is always equal to the sewage sludge counter-factual. Filled processes indicate by-products (energy or fertilizers) that avoid the production of marginal energy or marginal mineral fertilizers. MBT: mechanical biological treatment; UOL: use-on-land; WWTP: wastewater treatment plant; AD: anaerobic digestion

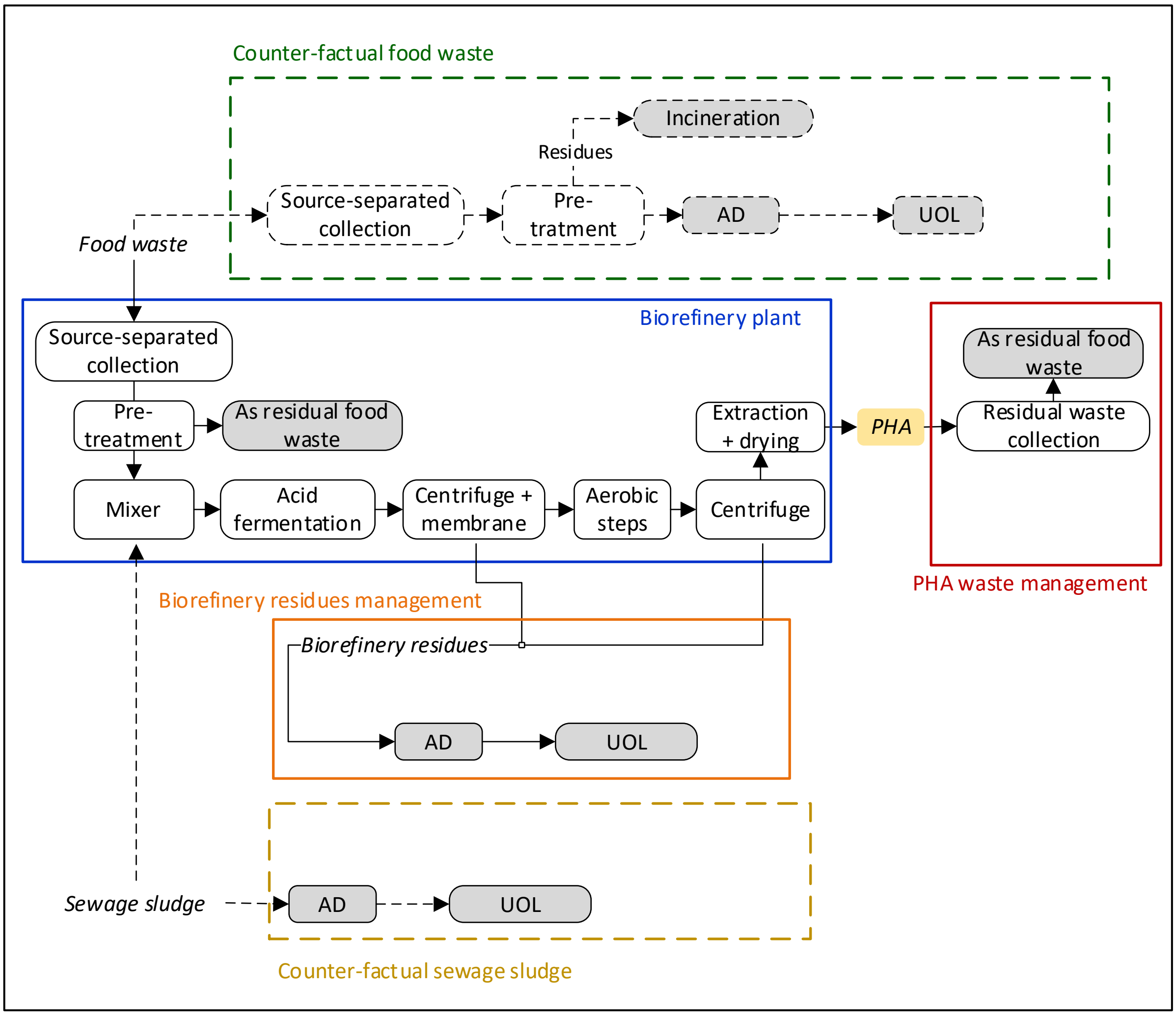

Figure 12: System boundaries of the alternative scenario "SS_AD_UOL" for Copenhagen. The PHA production process was divided into the plant itself (in blue), the treatment of the biorefinery residues (in orange), and the incineration/landfilling of the PHA (in red). The dotted lines indicate the food waste counter-factual (in green) and sewage sludge counter-factual (in yellow), which are modeled by subtracting them from the PHA production process. The treatment of the biorefinery residues is always equal to the sewage sludge counter-factual. Filled processes indicate by-products (energy or fertilizers) that avoid the production of marginal energy or marginal mineral fertilizers. MBT: mechanical biological treatment; UOL: use-on-land; WWTP: wastewater treatment plant; AD: anaerobic digestion

2.1.3 Lisbon

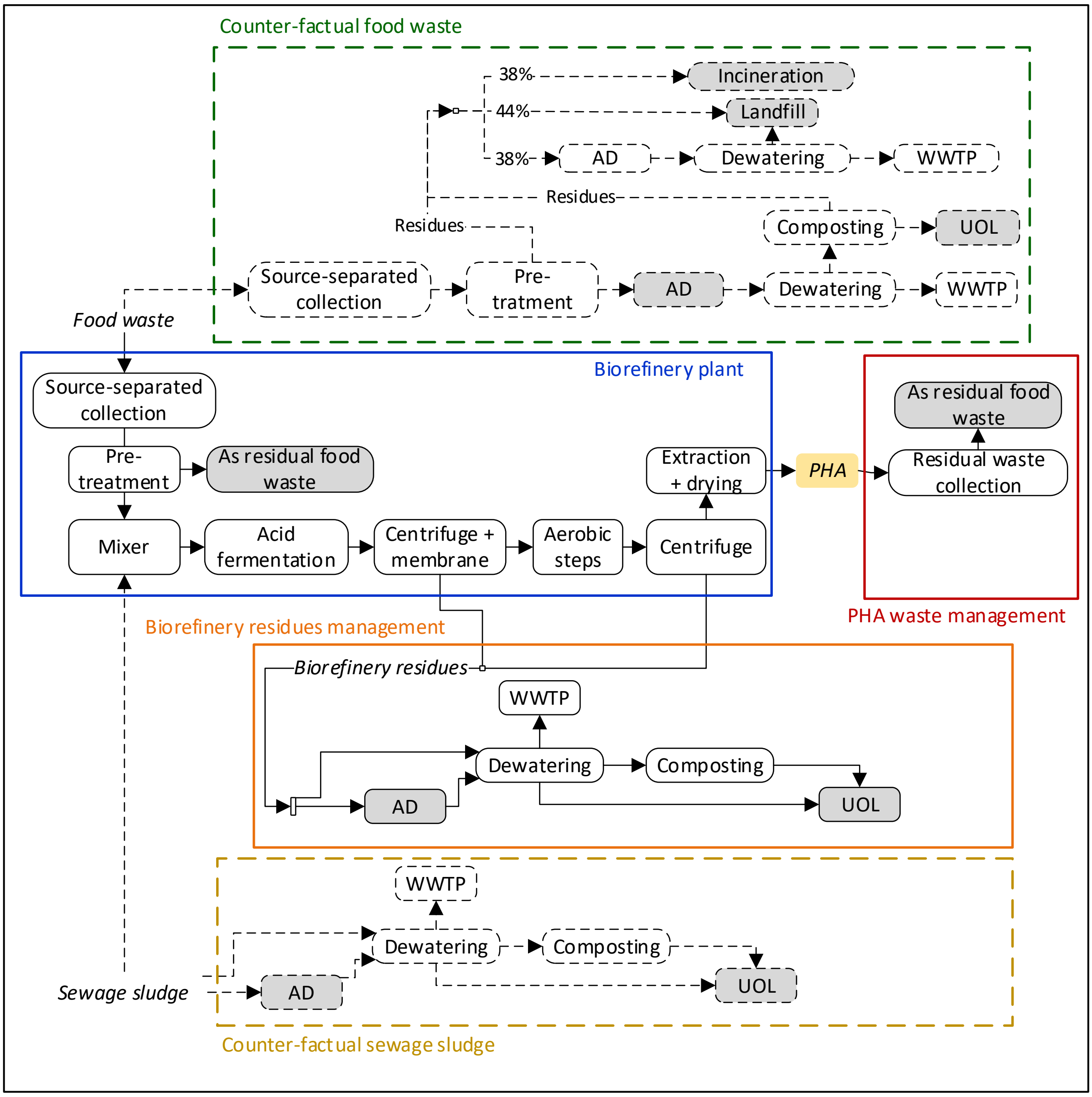

Figure 13: System boundaries of the alternative scenario "FW_sep." for Lisbon. The PHA production process was divided into the plant itself (in blue), the treatment of the biorefinery residues (in orange), and the incineration/landfilling of the PHA (in red). The dotted lines indicate the food waste counter-factual (in green) and sewage sludge counter-factual (in yellow), which are modeled by subtracting them from the PHA production process. The treatment of the biorefinery residues is always equal to the sewage sludge counter-factual. Filled processes indicate by-products (energy or fertilizers) that avoid the production of marginal energy or marginal mineral fertilizers. MBT: mechanical biological treatment; UOL: use-on-land; WWTP: wastewater treatment plant; AD: anaerobic digestion

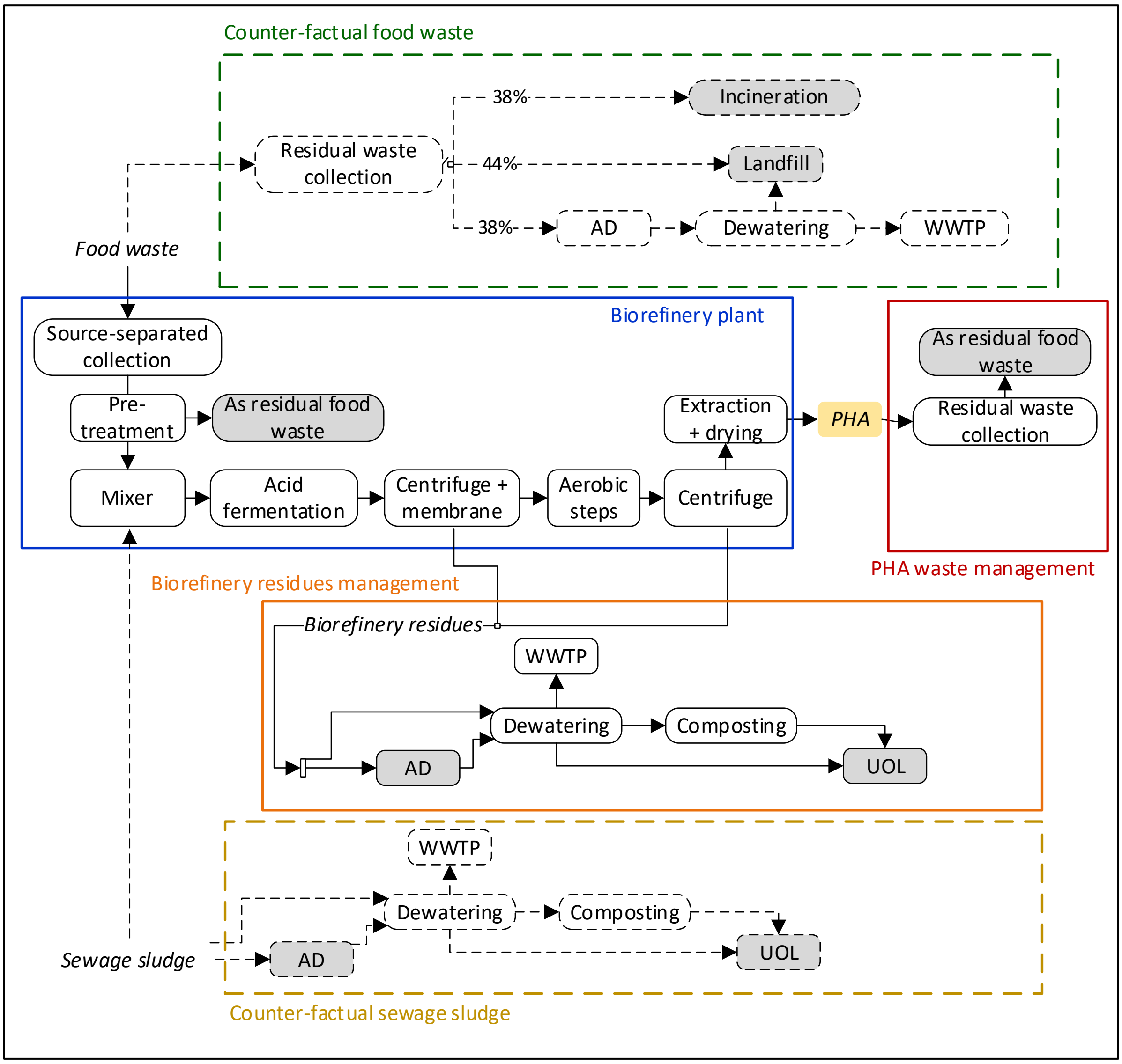

Figure 14: System boundaries of the alternative scenario "FW_residual." for Lisbon. The PHA production process was divided into the plant itself (in blue), the treatment of the biorefinery residues (in orange), and the incineration/landfilling of the PHA (in red). The dotted lines indicate the food waste counter-factual (in green) and sewage sludge counter-factual (in yellow), which are modeled by subtracting them from the PHA production process. The treatment of the biorefinery residues is always equal to the sewage sludge counter-factual. Filled processes indicate by-products (energy or fertilizers) that avoid the production of marginal energy or marginal mineral fertilizers. MBT: mechanical biological treatment; UOL: use-on-land; WWTP: wastewater treatment plant; AD: anaerobic digestion.

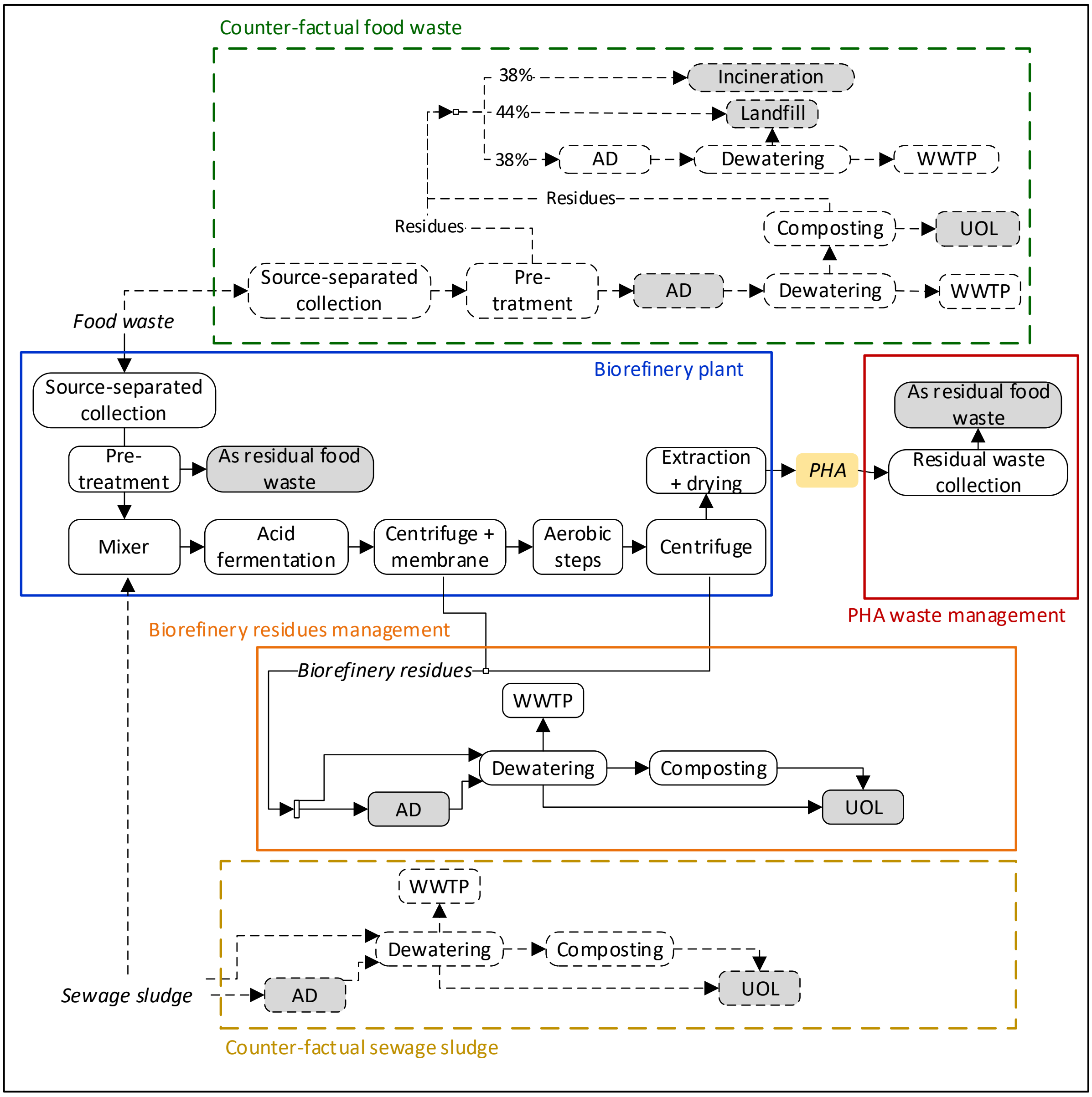

Figure 15: System boundaries of the alternative scenario "FW_AD." for Lisbon. The PHA production process was divided into the plant itself (in blue), the treatment of the biorefinery residues (in orange), and the incineration/landfilling of the PHA (in red). The dotted lines indicate the food waste counter-factual (in green) and sewage sludge counter-factual (in yellow), which are modeled by subtracting them from the PHA production process. The treatment of the biorefinery residues is always equal to the sewage sludge counter-factual. Filled processes indicate by-products (energy or fertilizers) that avoid the production of marginal energy or marginal mineral fertilizers. MBT: mechanical biological treatment; UOL: use-on-land; WWTP: wastewater treatment plant; AD: anaerobic digestion

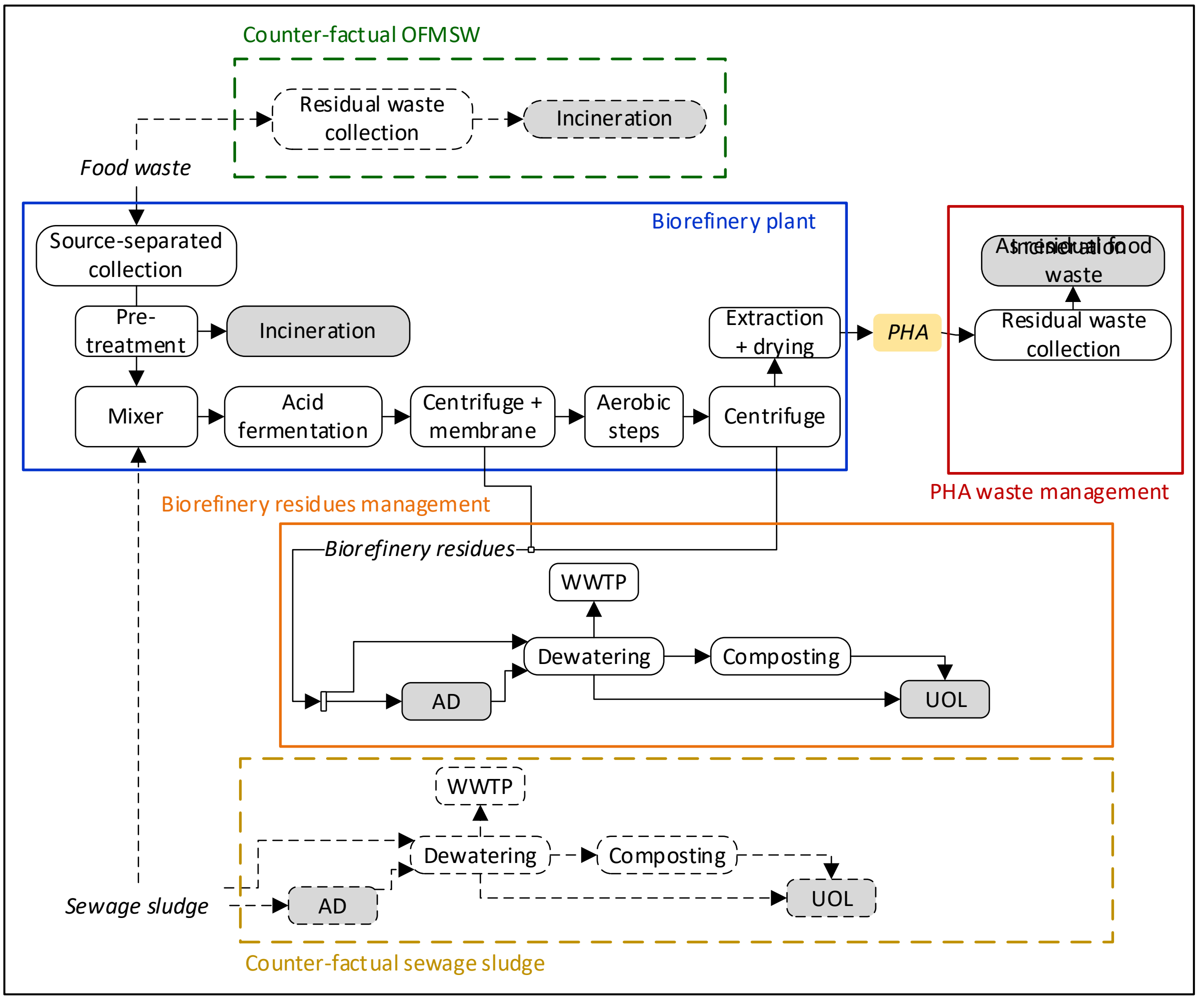

Figure 16: System boundaries of the alternative scenario "FW_Incl." for Lisbon. The PHA production process was divided into the plant itself (in blue), the treatment of the biorefinery residues (in orange), and the incineration/landfilling of the PHA (in red). The dotted lines indicate the food waste counter-factual (in green) and sewage sludge counter-factual (in yellow), which are modeled by subtracting them from the PHA production process. The treatment of the biorefinery residues is always equal to the sewage sludge counter-factual. Filled processes indicate by-products (energy or fertilizers) that avoid the production of marginal energy or marginal mineral fertilizers. MBT: mechanical biological treatment; UOL: use-on-land; WWTP: wastewater treatment plant; AD: anaerobic digestion

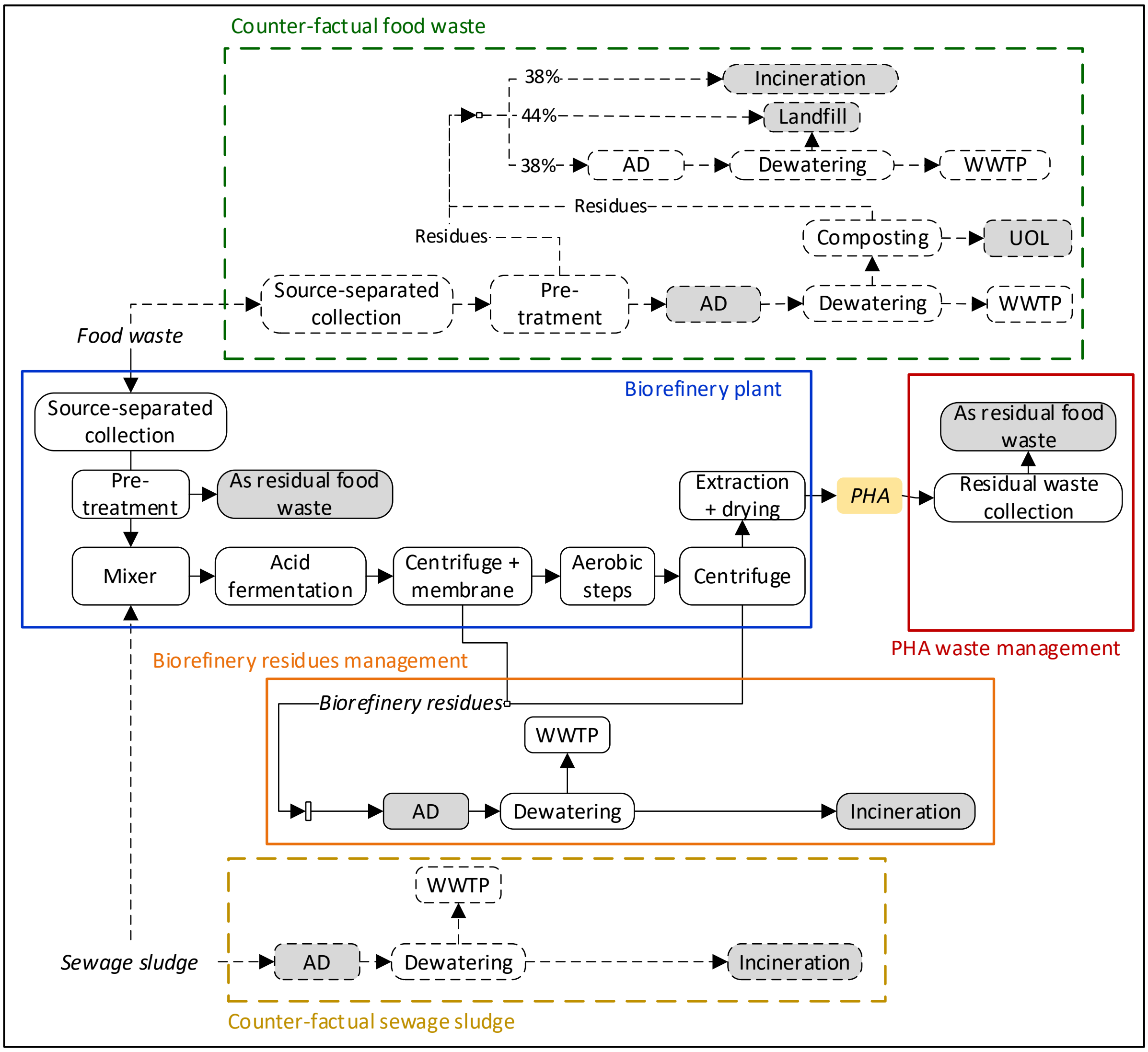

Figure 17: System boundaries of the alternative scenario "SS_AD_Inc." for Lisbon. The PHA production process was divided into the plant itself (in blue), the treatment of the biorefinery residues (in orange), and the incineration/landfilling of the PHA (in red). The dotted lines indicate the food waste counter-factual (in green) and sewage sludge counter-factual (in yellow), which are modeled by subtracting them from the PHA production process. The treatment of the biorefinery residues is always equal to the sewage sludge counter-factual. Filled processes indicate by-products (energy or fertilizers) that avoid the production of marginal energy or marginal mineral fertilizers. MBT: mechanical biological treatment; UOL: use-on-land; WWTP: wastewater treatment plant; AD: anaerobic digestion

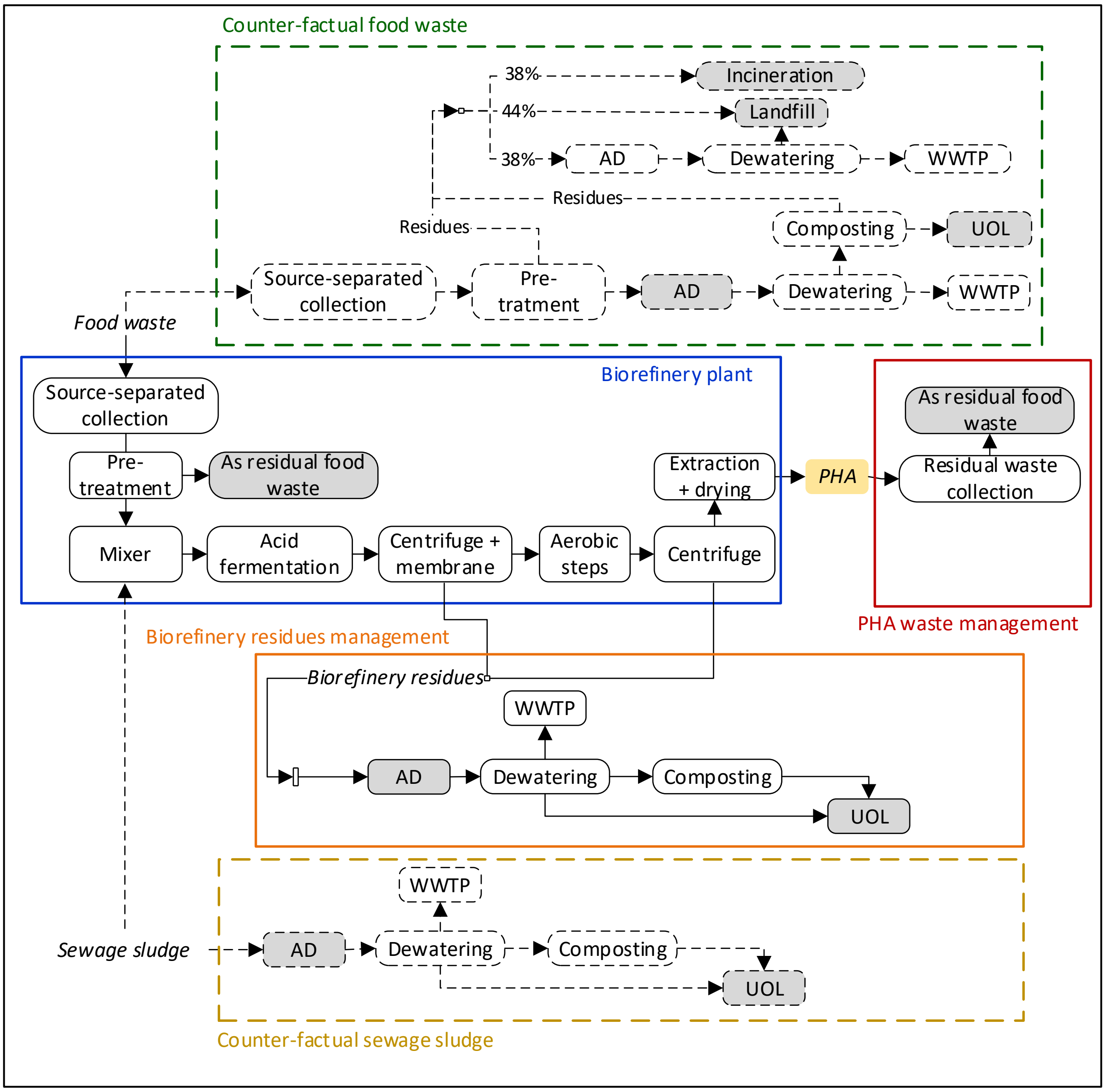

Figure 18: System boundaries of the alternative scenario "SS_AD_UOL" for Lisbon. The PHA production process was divided into the plant itself (in blue), the treatment of the biorefinery residues (in orange), and the incineration/landfilling of the PHA (in red). The dotted lines indicate the food waste counter-factual (in green) and sewage sludge counter-factual (in yellow), which are modeled by subtracting them from the PHA production process. The treatment of the biorefinery residues is always equal to the sewage sludge counter-factual. Filled processes indicate by-products (energy or fertilizers) that avoid the production of marginal energy or marginal mineral fertilizers. MBT: mechanical biological treatment; UOL: use-on-land; WWTP: wastewater treatment plant; AD: anaerobic digestion

2.1.4 South Wales

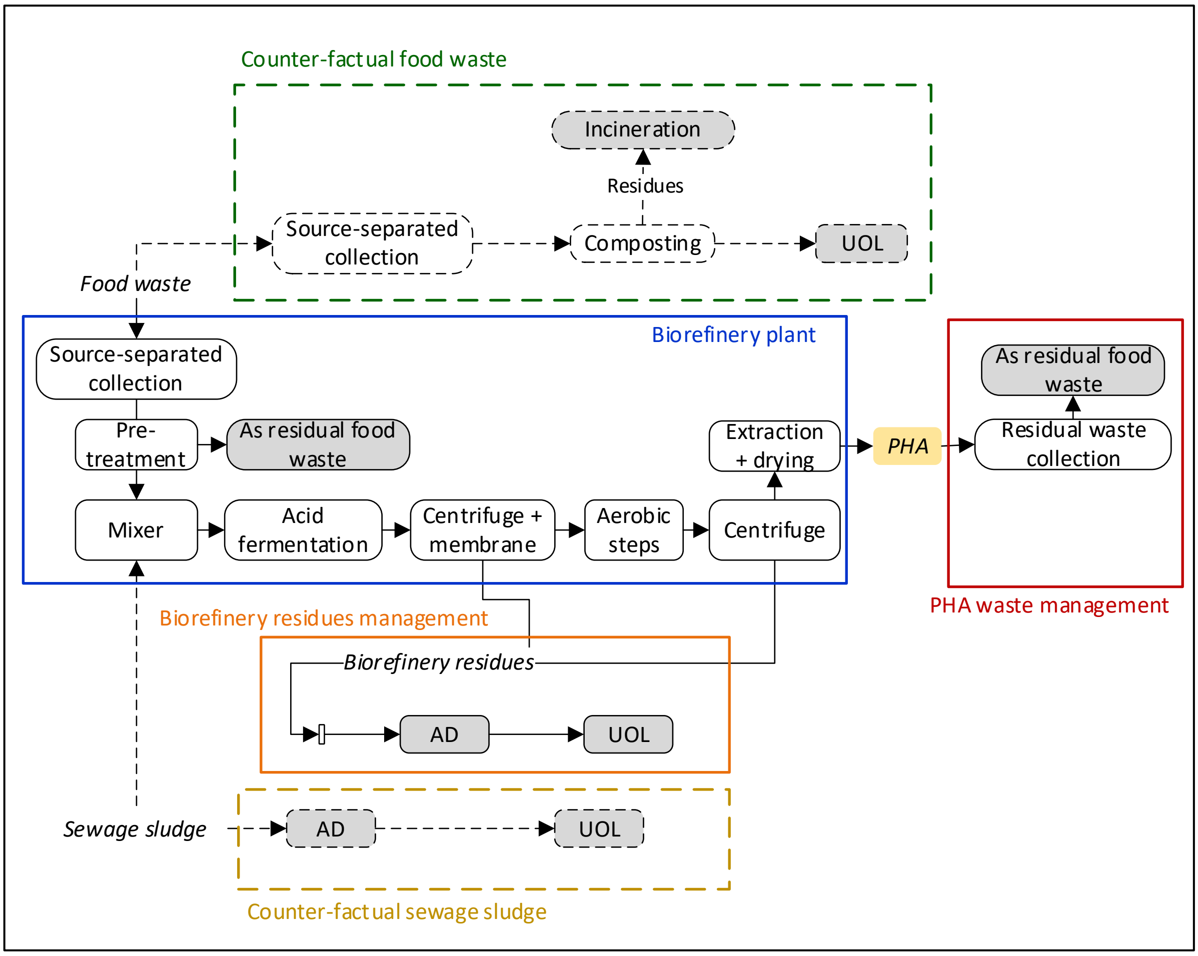

Figure 19: System boundaries of the alternative scenario "FW_sep." for South Wales. The PHA production process was divided into the plant itself (in blue), the treatment of the biorefinery residues (in orange), and the incineration/landfilling of the PHA (in red). The dotted lines indicate the food waste counter-factual (in green) and sewage sludge counter-factual (in yellow), which are modeled by subtracting them from the PHA production process. The treatment of the biorefinery residues is always equal to the sewage sludge counter-factual. Filled processes indicate by-products (energy or fertilizers) that avoid the production of marginal energy or marginal mineral fertilizers. MBT: mechanical biological treatment; UOL: use-on-land; WWTP: wastewater treatment plant; AD: anaerobic digestion

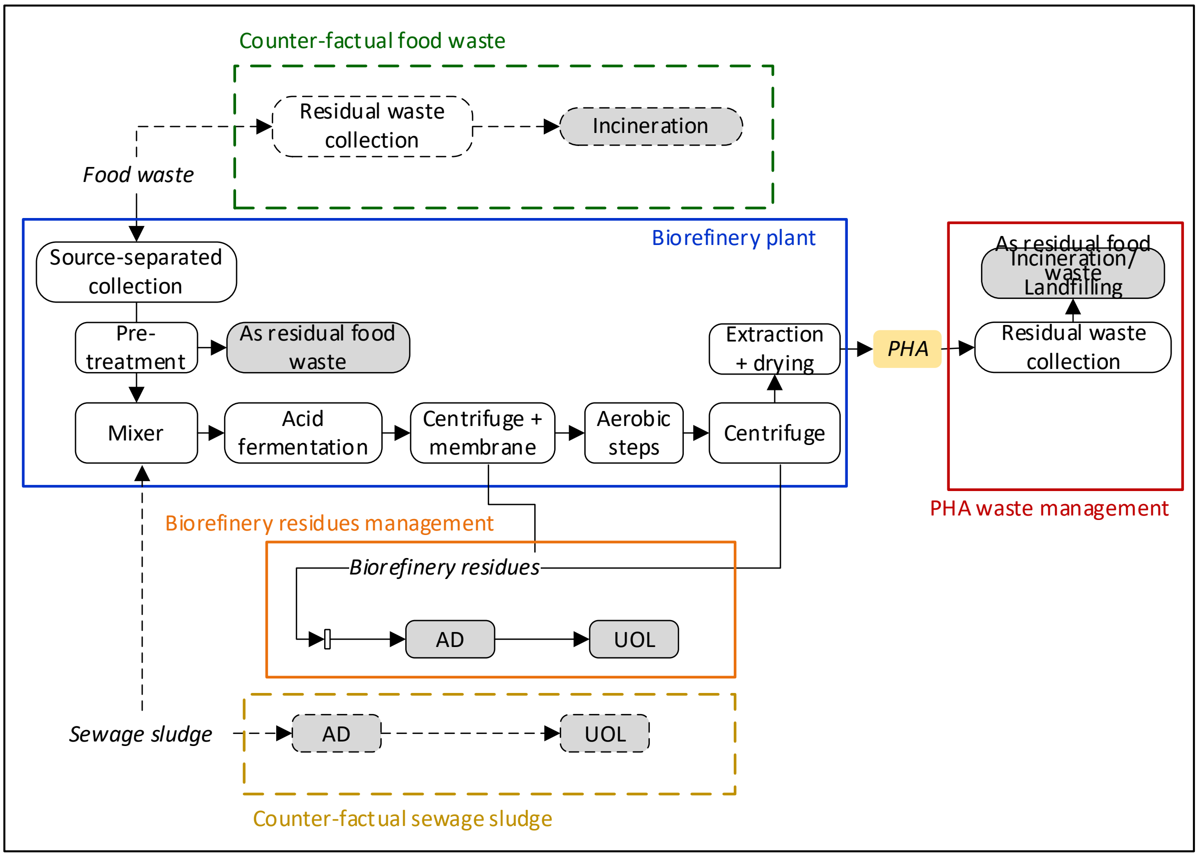

Figure 20: System boundaries of the alternative scenario "FW_residual." for South Wales. The PHA production process was divided into the plant itself (in blue), the treatment of the biorefinery residues (in orange), and the incineration/landfilling of the PHA (in red). The dotted lines indicate the food waste counter-factual (in green) and sewage sludge counter-factual (in yellow), which are modeled by subtracting them from the PHA production process. The treatment of the biorefinery residues is always equal to the sewage sludge counter-factual. Filled processes indicate by-products (energy or fertilizers) that avoid the production of marginal energy or marginal mineral fertilizers. MBT: mechanical biological treatment; UOL: use-on-land; WWTP: wastewater treatment plant; AD: anaerobic digestion.

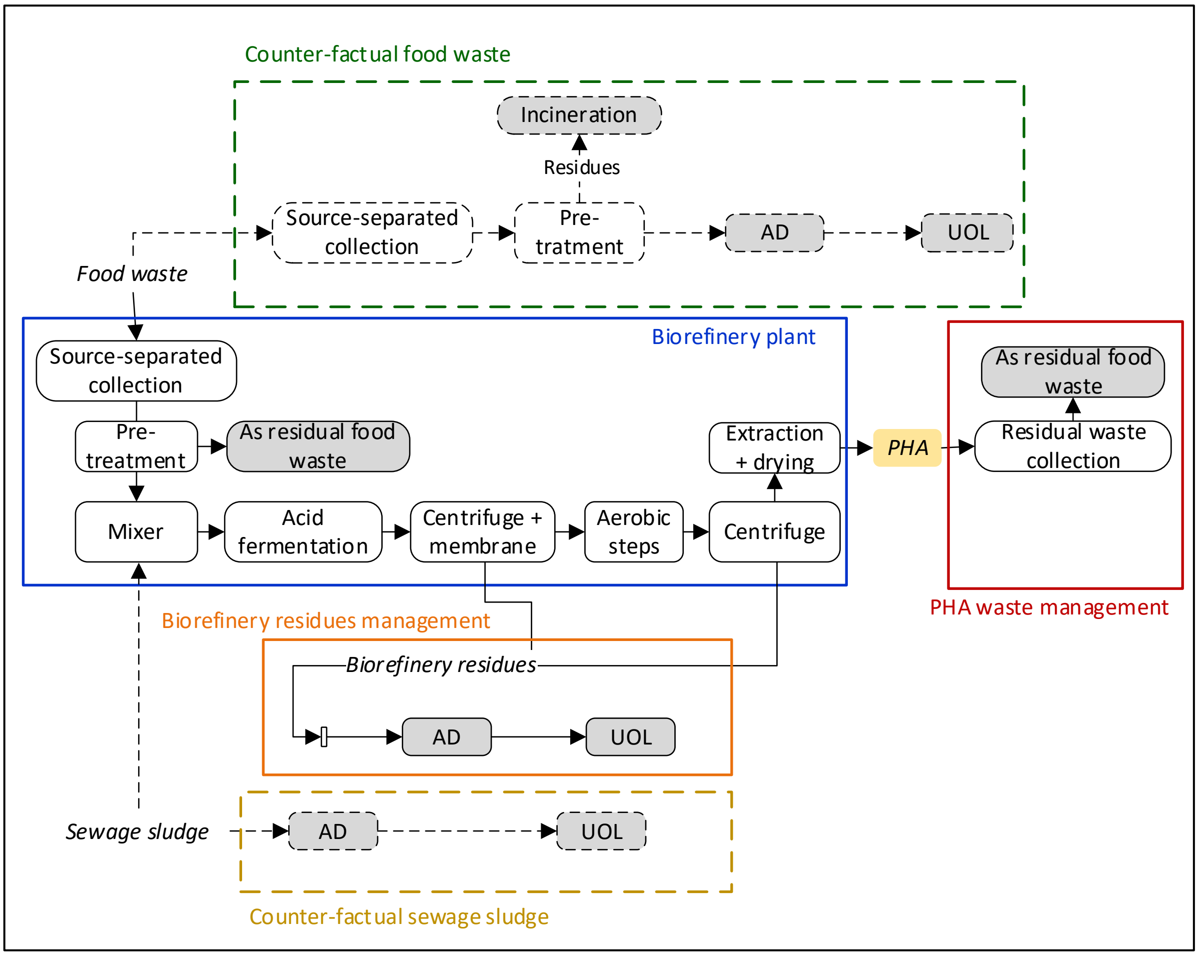

Figure 21: System boundaries of the alternative scenario "FW_AD." for South Wales. The PHA production process was divided into the plant itself (in blue), the treatment of the biorefinery residues (in orange), and the incineration/landfilling of the PHA (in red). The dotted lines indicate the food waste counter-factual (in green) and sewage sludge counter-factual (in yellow), which are modeled by subtracting them from the PHA production process. The treatment of the biorefinery residues is always equal to the sewage sludge counter-factual. Filled processes indicate by-products (energy or fertilizers) that avoid the production of marginal energy or marginal mineral fertilizers. MBT: mechanical biological treatment; UOL: use-on-land; WWTP: wastewater treatment plant; AD: anaerobic digestion

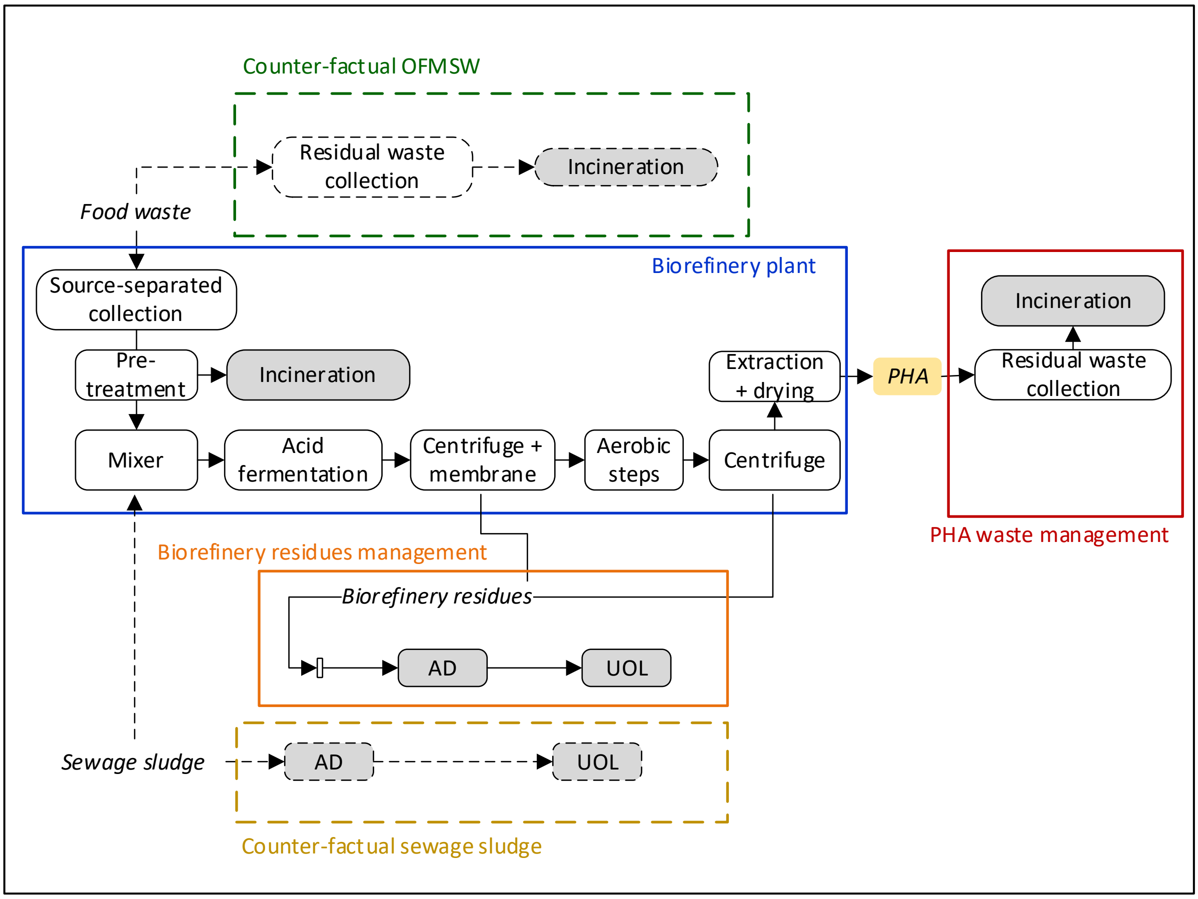

Figure 22: System boundaries of the alternative scenario "FW_Incl." for South Wales. The PHA production process was divided into the plant itself (in blue), the treatment of the biorefinery residues (in orange), and the incineration/landfilling of the PHA (in red). The dotted lines indicate the food waste counter-factual (in green) and sewage sludge counter-factual (in yellow), which are modeled by subtracting them from the PHA production process. The treatment of the biorefinery residues is always equal to the sewage sludge counter-factual. Filled processes indicate by-products (energy or fertilizers) that avoid the production of marginal energy or marginal mineral fertilizers. MBT: mechanical biological treatment; UOL: use-on-land; WWTP: wastewater treatment plant; AD: anaerobic digestion

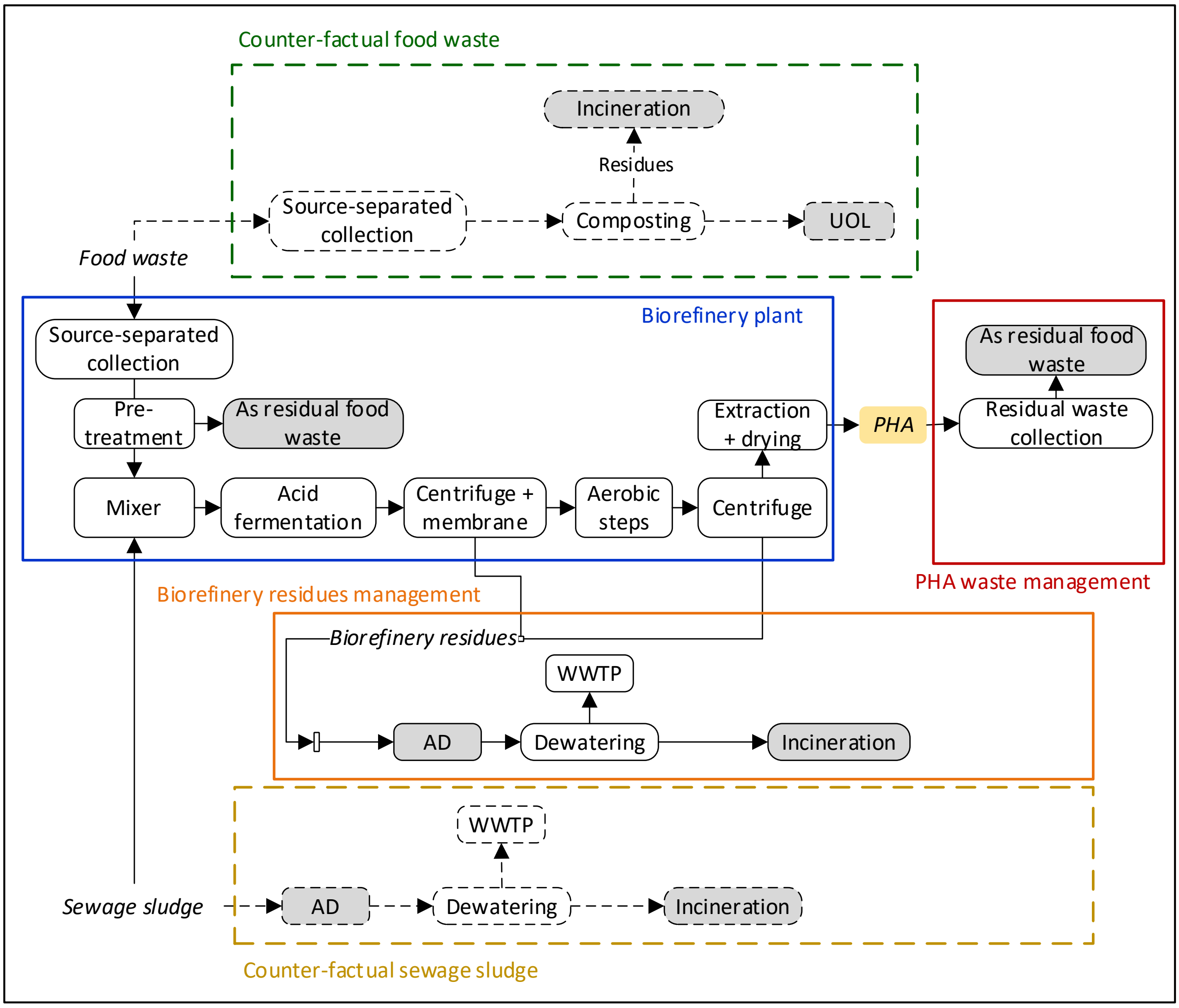

Figure 23: System boundaries of the alternative scenario "SS_AD_Inc." for South Wales. The PHA production process was divided into the plant itself (in blue), the treatment of the biorefinery residues (in orange), and the incineration/landfilling of the PHA (in red). The dotted lines indicate the food waste counter-factual (in green) and sewage sludge counter-factual (in yellow), which are modeled by subtracting them from the PHA production process. The treatment of the biorefinery residues is always equal to the sewage sludge counter-factual. Filled processes indicate by-products (energy or fertilizers) that avoid the production of marginal energy or marginal mineral fertilizers. MBT: mechanical biological treatment; UOL: use-on-land; WWTP: wastewater treatment plant; AD: anaerobic digestion

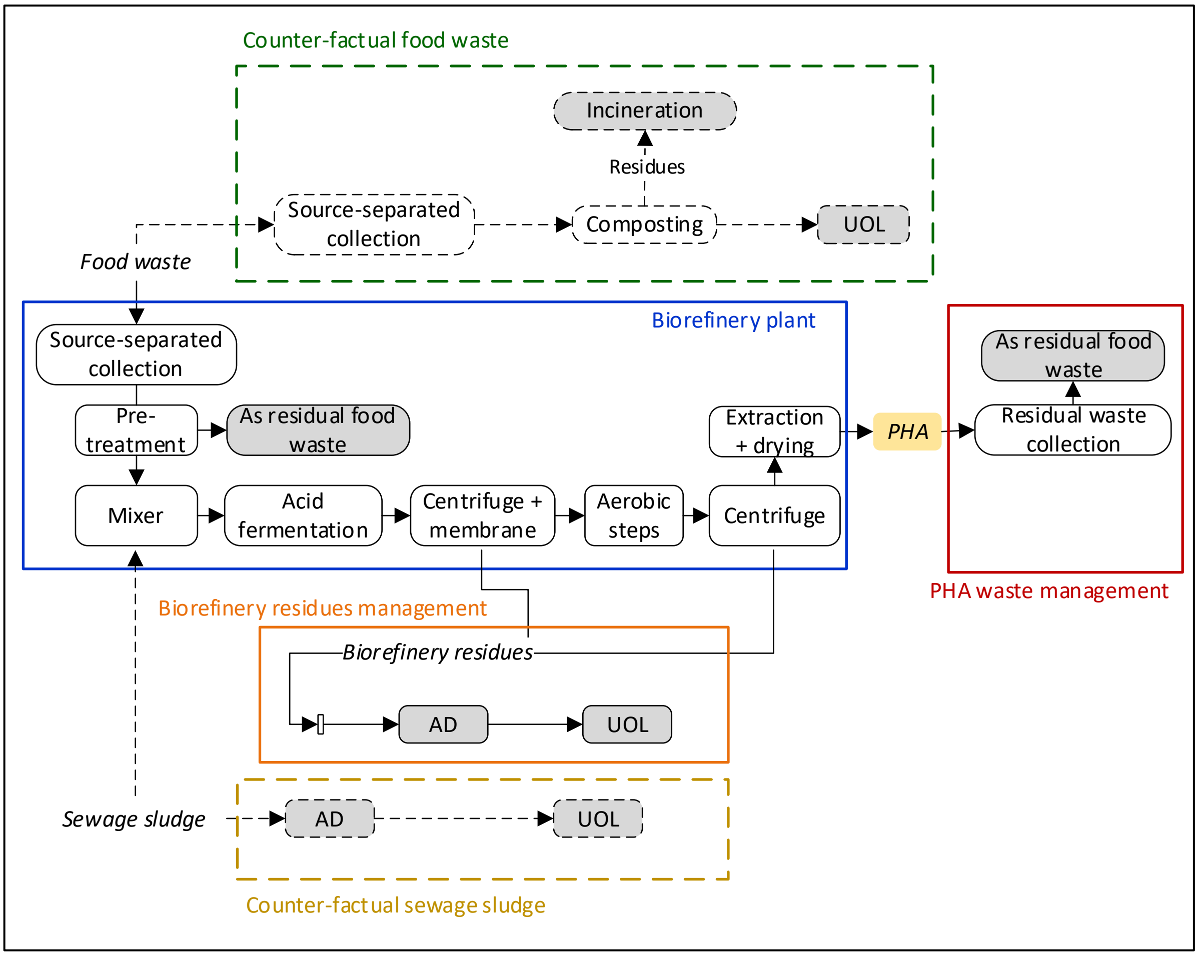

Figure 24: System boundaries of the alternative scenario "SS_AD_UOL" for South Wales. The PHA production process was divided into the plant itself (in blue), the treatment of the biorefinery residues (in orange), and the incineration/landfilling of the PHA (in red). The dotted lines indicate the food waste counter-factual (in green) and sewage sludge counter-factual (in yellow), which are modeled by subtracting them from the PHA production process. The treatment of the biorefinery residues is always equal to the sewage sludge counter-factual. Filled processes indicate by-products (energy or fertilizers) that avoid the production of marginal energy or marginal mineral fertilizers. MBT: mechanical biological treatment; UOL: use-on-land; WWTP: wastewater treatment plant; AD: anaerobic digestion

2.1.5 Trento

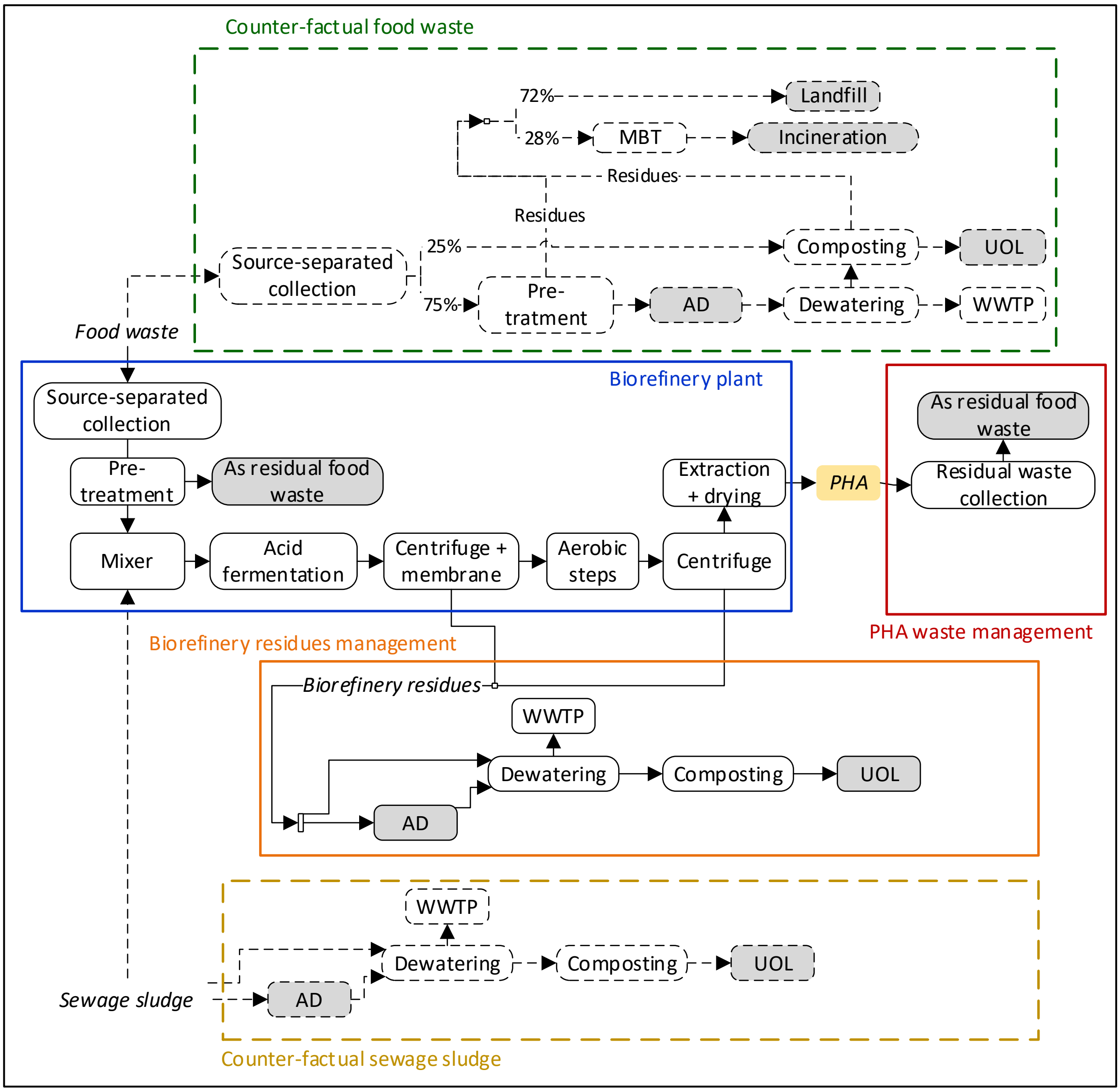

Figure 25: System boundaries of the alternative scenario "FW_sep." for Lisbon. The PHA production process was divided into the plant itself (in blue), the treatment of the biorefinery residues (in orange), and the incineration/landfilling of the PHA (in red). The dotted lines indicate the food waste counter-factual (in green) and sewage sludge counter-factual (in yellow), which are modeled by subtracting them from the PHA production process. The treatment of the biorefinery residues is always equal to the sewage sludge counter-factual. Filled processes indicate by-products (energy or fertilizers) that avoid the production of marginal energy or marginal mineral fertilizers. MBT: mechanical biological treatment; UOL: use-on-land; WWTP: wastewater treatment plant; AD: anaerobic digestion

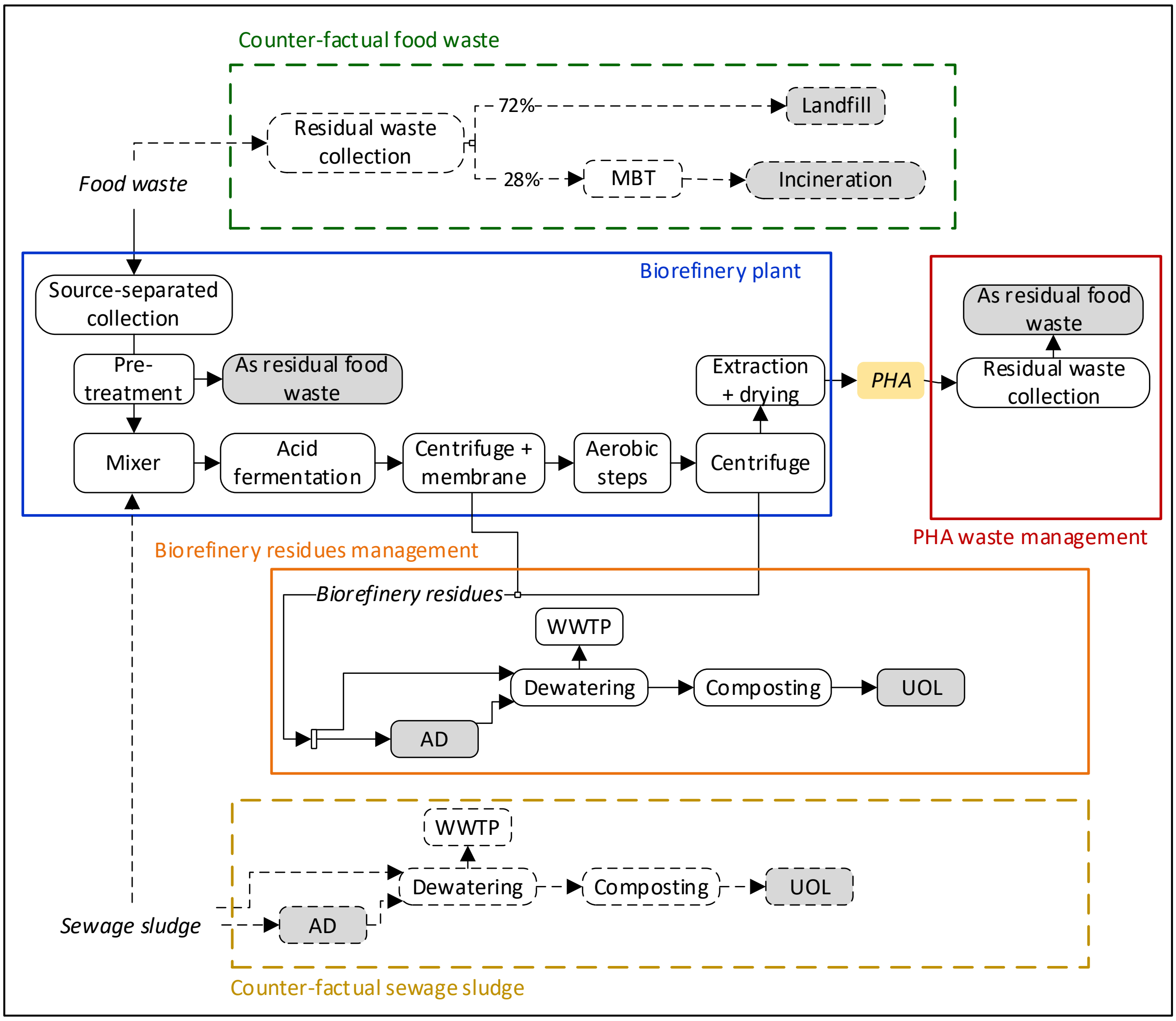

Figure 26: System boundaries of the alternative scenario "FW_residual." for Lisbon. The PHA production process was divided into the plant itself (in blue), the treatment of the biorefinery residues (in orange), and the incineration/landfilling of the PHA (in red). The dotted lines indicate the food waste counter-factual (in green) and sewage sludge counter-factual (in yellow), which are modeled by subtracting them from the PHA production process. The treatment of the biorefinery residues is always equal to the sewage sludge counter-factual. Filled processes indicate by-products (energy or fertilizers) that avoid the production of marginal energy or marginal mineral fertilizers. MBT: mechanical biological treatment; UOL: use-on-land; WWTP: wastewater treatment plant; AD: anaerobic digestion.

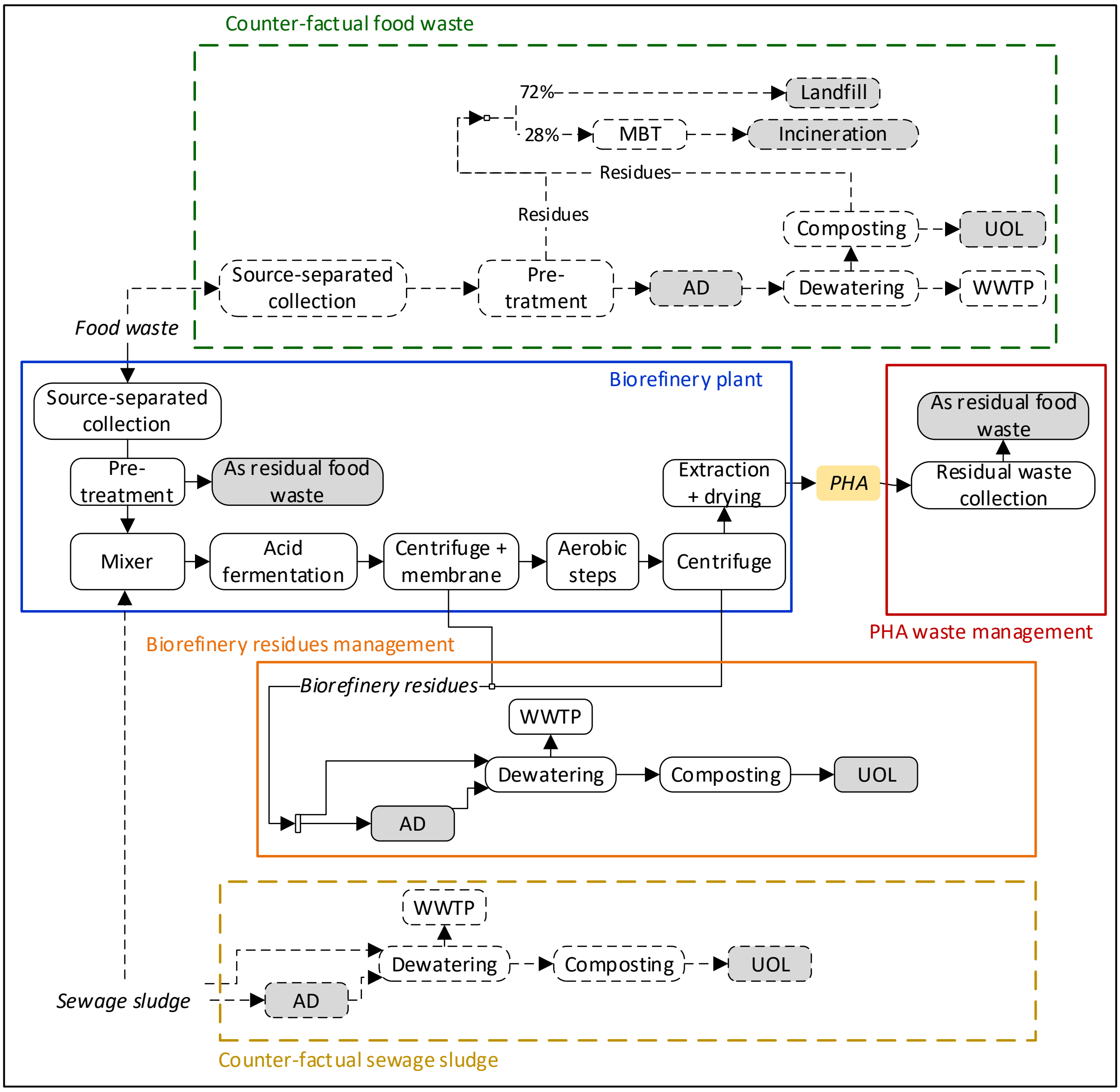

Figure 27: System boundaries of the alternative scenario "FW_AD." for Lisbon. The PHA production process was divided into the plant itself (in blue), the treatment of the biorefinery residues (in orange), and the incineration/landfilling of the PHA (in red). The dotted lines indicate the food waste counter-factual (in green) and sewage sludge counter-factual (in yellow), which are modeled by subtracting them from the PHA production process. The treatment of the biorefinery residues is always equal to the sewage sludge counter-factual. Filled processes indicate by-products (energy or fertilizers) that avoid the production of marginal energy or marginal mineral fertilizers. MBT: mechanical biological treatment; UOL: use-on-land; WWTP: wastewater treatment plant; AD: anaerobic digestion

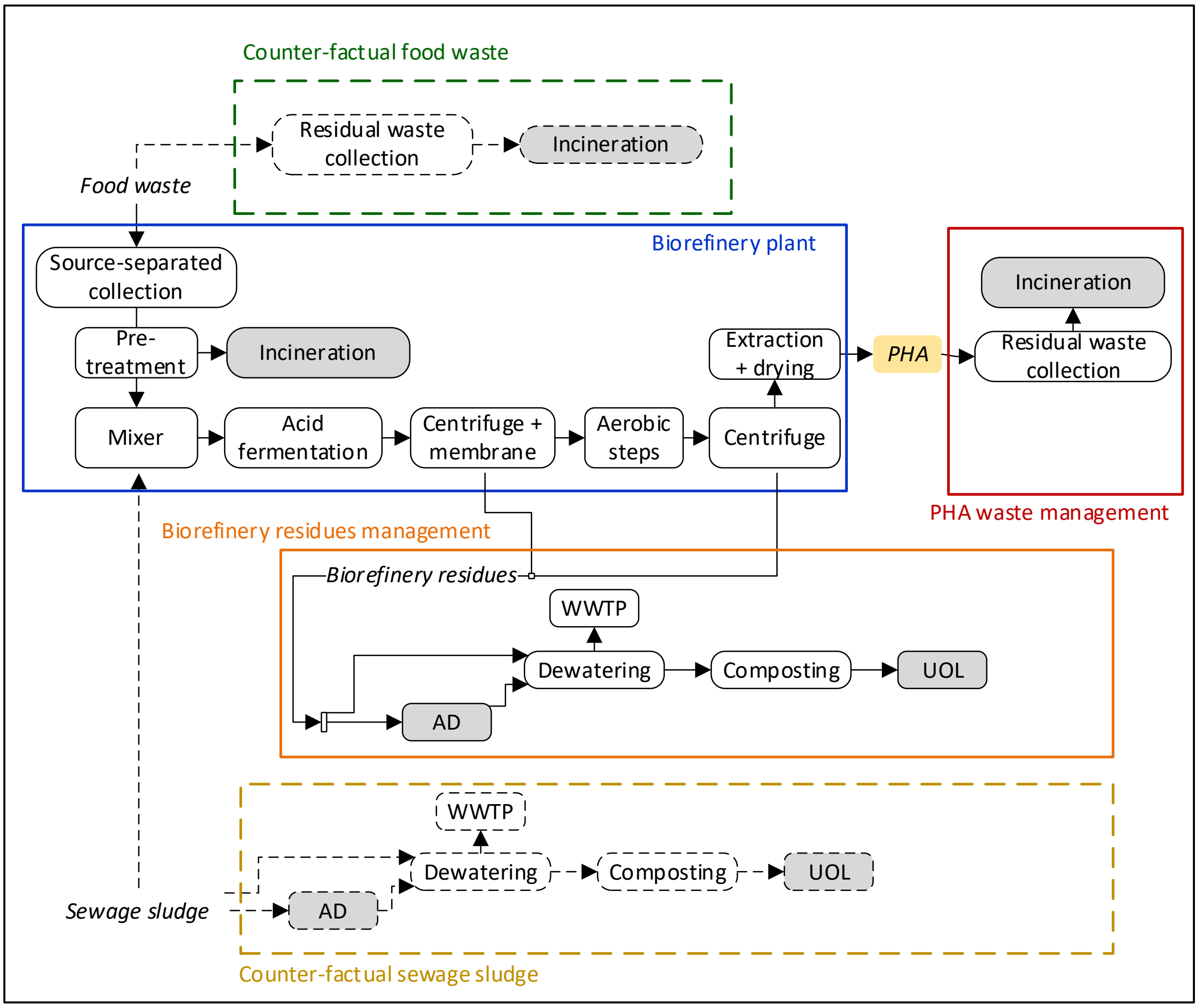

Figure 28: System boundaries of the alternative scenario "FW_Incl." for Lisbon. The PHA production process was divided into the plant itself (in blue), the treatment of the biorefinery residues (in orange), and the incineration/landfilling of the PHA (in red). The dotted lines indicate the food waste counter-factual (in green) and sewage sludge counter-factual (in yellow), which are modeled by subtracting them from the PHA production process. The treatment of the biorefinery residues is always equal to the sewage sludge counter-factual. Filled processes indicate by-products (energy or fertilizers) that avoid the production of marginal energy or marginal mineral fertilizers. MBT: mechanical biological treatment; UOL: use-on-land; WWTP: wastewater treatment plant; AD: anaerobic digestion

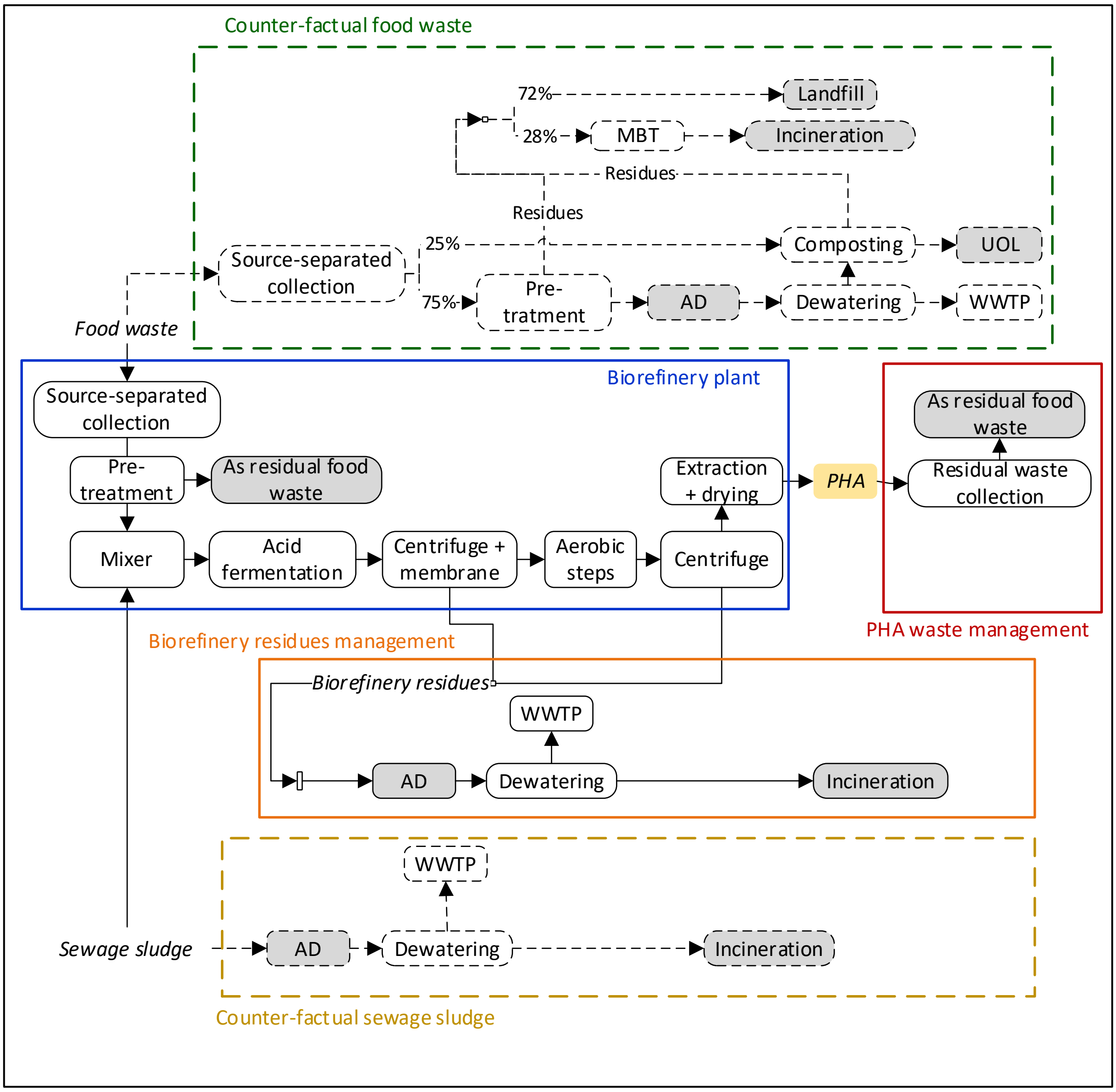

Figure 29: System boundaries of the alternative scenario "SS_AD_Inc." for Lisbon. The PHA production process was divided into the plant itself (in blue), the treatment of the biorefinery residues (in orange), and the incineration/landfilling of the PHA (in red). The dotted lines indicate the food waste counter-factual (in green) and sewage sludge counter-factual (in yellow), which are modeled by subtracting them from the PHA production process. The treatment of the biorefinery residues is always equal to the sewage sludge counter-factual. Filled processes indicate by-products (energy or fertilizers) that avoid the production of marginal energy or marginal mineral fertilizers. MBT: mechanical biological treatment; UOL: use-on-land; WWTP: wastewater treatment plant; AD: anaerobic digestion

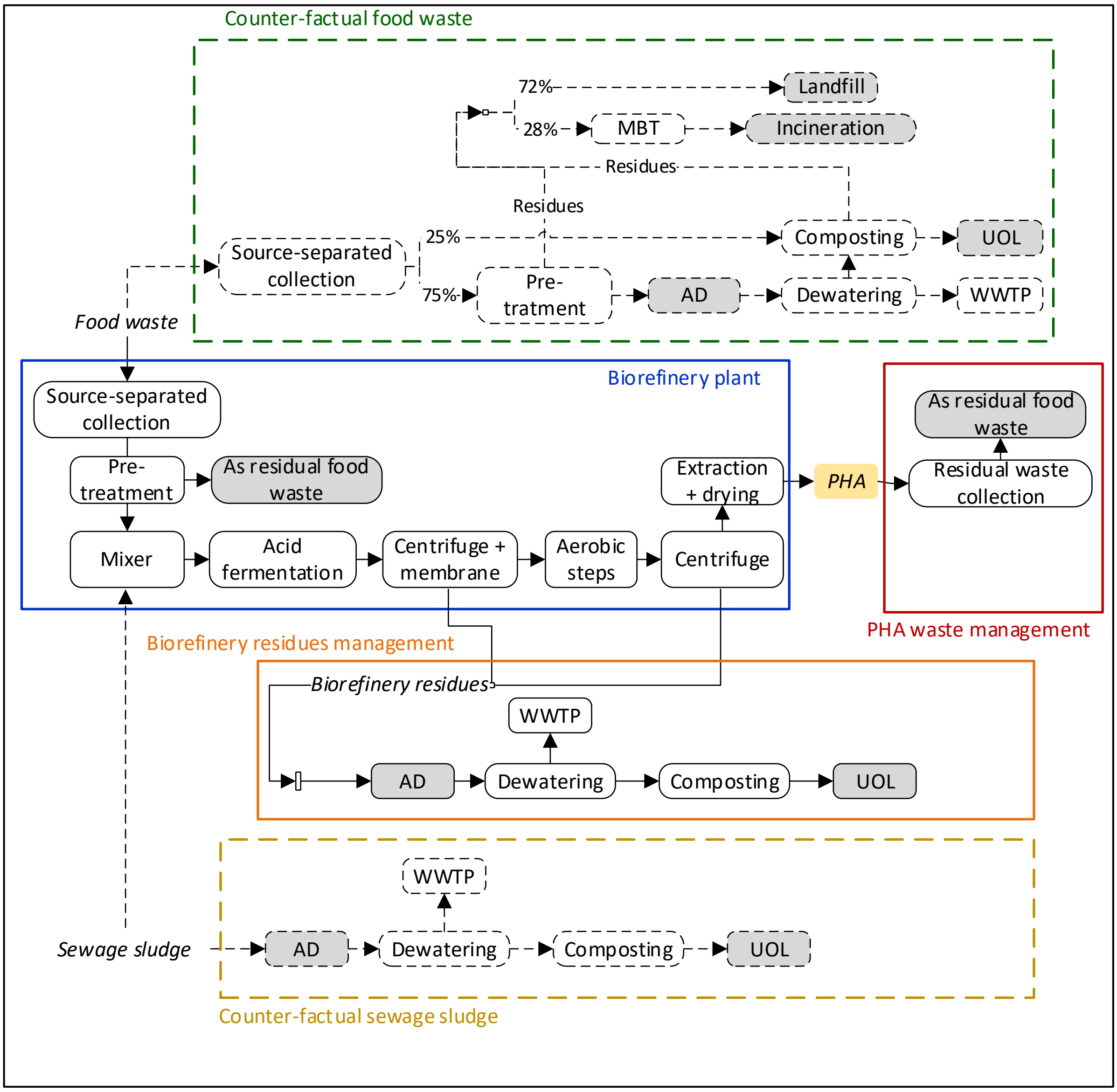

Figure 30: System boundaries of the alternative scenario "SS_AD_UOL" for Lisbon. The PHA production process was divided into the plant itself (in blue), the treatment of the biorefinery residues (in orange), and the incineration/landfilling of the PHA (in red). The dotted lines indicate the food waste counter-factual (in green) and sewage sludge counter-factual (in yellow), which are modeled by subtracting them from the PHA production process. The treatment of the biorefinery residues is always equal to the sewage sludge counter-factual. Filled processes indicate by-products (energy or fertilizers) that avoid the production of marginal energy or marginal mineral fertilizers. MBT: mechanical biological treatment; UOL: use-on-land; WWTP: wastewater treatment plant; AD: anaerobic digestion

3 Life Cycle Inventory

3.1 Summary of the data presented

Table 1 lists the process included in the system boundaries of the data needed to model the LCA and the LCC for each process. Each process is described in more details in the following sections.

All the background processes were based on ecoinvent 3.6 consequential.

Table 1: Data needed to model the life cycle assessment (LCA) and the life cycle costing (LCC).

Process	Data
Current municipal food waste and sewage sludge management	• Current (in 2018) management of source-separated food waste in the different clusters • Current (in 2018) management of non-source-separated food waste (i.e. residual waste) in the different clusters

	• Current (in 2018) management of sewage sludge in the different clusters
Municipal food waste and sewage sludge composition	• Chemical composition • Low heating value
Sewage sludge composition	• Chemical composition • Low heating value

Municipal food waste collection	• Collection of source-separated food waste
	  o Diesel consumption
	  o Cost
	• Collection of residual municipal solid waste
	  o Diesel consumption
	  o Cost

Biorefinery producing PHA	• Efficiency • Mass balance • Energy consumption • Ancillary materials consumption • Costs

Anaerobic digestion (food waste and sewage sludge)	• Pre-treatment of the source-separated municipal food waste (efficiency, energy consumption, and costs)
	• Methane generation rate (for food waste and sewage sludge)
	• Water content in the digester
	• VS and C degradation (for food waste and sewage sludge)
	• Diesel consumption
	• Energy consumption
	• Methane leakage
	• Costs
	• Biogas utilization
	  o Combined heat and power plant (efficiency, methane leakage, direct emissions, and costs)
	  o Biogas upgrading (efficiency, methane leakage, direct emissions, energy and water consumption, and costs)

Composting (food waste and sewage sludge)	• VS, C, and N degradation • Direct emissions • Electricity consumption • Water content compost • Costs
Dewatering of the digestate	• Energy and ancillary material consumption • Water content of the solid fraction • Mass balance • Costs
Treatment of the reject water from the dewatering	• Energy and ancillary material consumption • Direct emissions • Mass balance • Costs
Incineration (food waste and sewage sludge)	• Gross energy efficiency • Internal energy consumption • Ancillary material consumption • Process and input specific emissions • Costs
Use-on-land (composted food waste and sewage sludge, raw digestate from food waste, and raw sewage sludge)	• Emissions to air, water, and soil (divided into compost, digestate and raw sludge) • Diesel consumption • Costs of spreading
Mechanical biological treatments	• Energy and ancillary material consumption • Efficiency • Emissions • Costs
Landfilling	• Gas collection rate • Gas flaring rate • Costs
Consumed and avoided energy	• Marginal electricity composition • Marginal space heating composition • Costs
Avoided fertilizers	• Use-on-land • Heavy metal content • N marginal fertilizer composition • P marginal fertilizer composition • K marginal fertilizer composition • Costs

Transport	• Type of truck • Distances • Costs
Salary	•
PHA from first-generation biomass	• First-generation biomass consumption • Energy and ancillary material consumption • Costs
Fossil plastic	• Types of fossil plastic that are competitive with PHA • Modeled processes • Costs

3.2 Economic data

All the economic data were harmonized to EUR2019 using the Harmonised Index of Consumer Prices (Eurostat, 2018a). Furthermore, all the capital expenditures (CAPEX) were annualized as in Cimpan et al. (2016a) considering the lifetime of the buildings and the national interest rate: $CAPEX = tot\,CAPEX * CRF$, where CRF is the capital recovery factor calculated as $CRF = \frac{i*(1+i)^n}{[(1+i)^n-1]}$, where *i* is the interest rate and *n* the lifetime. A 5% interest rate and 20 years lifetime was assumed for all the plants based on as in Cimpan et al. (2016a).

Finally, Table 2 shows the cost of the insurance and maintenance that need to be paid yearly in all the processes involving a CAPEX (e.g. anaerobic digestion plant, incineration plant, dewatering plant).

Table 2: Insurance and maintenance assumed for all the capital expenditures (CAPEX) in the model modeled with a triangular uncertainty distribution.

	Unit	Mode	Min	Max	Reference
Insurance	% CAPEX	1.0%	0.5%	1.5%	(Cimpan et al., 2016; Martinez-Sanchez et al., 2016, 2015; Slorach et al., 2019; Tonini et al., 2019)
Maintenance	% CAPEX	2.7%	2.0%	3.4%	(Energinet, 2019; Iaboni and De Stefanis, 2007; Martinez-Sanchez et al., 2015; Slorach et al., 2019; Tonini et al., 2019)

3.3 How are the data aggregated in the results

The contribution analysis in the article (Fig. 4 in the main article) shows the results divided per grouped processes. Table 3 clarified the processes included in each grouped process.

Table 3: Processes included in the grouped processes in the contribution analyses in Fig. 4 of the main article. MBT: mechanical biological treatment, AD: anaerobic digestion

Grouped processes	What is it included
PHA refinery	• Pre-treatment of the food waste sent to the bio-refinery • Capital good of the bio-refinery • Acid fermentation, aerobic steps, centrifuges, filtration, extraction, and drying
Collection	• Collection of the source-separated food waste (both sent to the bio-refinery and in the food waste counter-factual) • Collection of the residual waste (in the food waste counter-factual)
Direct AD	• Pre-treatment of the source-separated food waste (food waste counter-factual) • AD reactors, including CH_4 leaking and capital goods (biorefinery residues, food waste counter-factual, sewage sludge counter-factual)
Biogas use and avoided energy	• Biogas combustion in a CHP engine, including the energy avoided by the biogas combustion (biorefinery residues, food waste counter-factual, sewage sludge counter-factual) • Biogas upgrading, including the natural gas production and combustion avoided by the biomethane (biorefinery residues, food waste counter-factual, sewage sludge counter-factual)
Composting	• Composting, including capital goods (biorefinery residues, food waste counter-factual, sewage sludge counter-factual)

UOL	• Direct emissions due to the use on agricultural fields of the compost/digestate/sewage sludge (biorefinery residues, food waste counter-factual, sewage sludge counter-factual) • Avoided mineral fertilizers due to the use on agricultural fields of the compost/digestate/sewage sludge
Incineration + MBT	• Incineration plants (biorefinery residues, food waste counter-factual, sewage sludge counter-factual) • MBT plants (biorefinery residues, food waste counter-factual, sewage sludge counter-factual)
Avoided energy (from incineration)	• Avoided energy due to the energy generated in the incineration plants (biorefinery residues, food waste counter-factual, sewage sludge counter-factual)
Landfill	• Landfills (biorefinery residues, food waste counter-factual, sewage sludge counter-factual)
WWTP + dewatering	• Dewatering process (biorefinery residues, food waste counter-factual, sewage sludge counter-factual) • Wastewater treatment plants (biorefinery residues, food waste counter-factual, sewage sludge counter-factual)
Waste PHA	• Management of the PHA waste that is treated either as in the residual food waste, including direct emissions and avoided energy. The specific treatment depends on the alternative scenario and in the cluster.

3.4 Current municipal food waste and sewage sludge management

This section describes the current (in 2018) management of municipal food waste and sewage sludge in the different clusters. The current management of the source-separated food waste represents the counter-factual of food waste in the alternative scenarios "FW_sep.", "SS_AD_Inc", and "SS_AD_UOL". The current management of the residual food waste represents the counter-factual of food waste in the alternative scenario "FW_residual". The current management of the sewage sludge represents the counter-factual of sewage sludge in the alternative scenario "FW_sep.", "FW_residual", "FW_AD", "FW_Inc".

3.4.1 Source-separated and residual food waste

Table 4 and Table 5 show all the steps included in the current management of the source-separated and residual food waste in the different clusters (and the sections of this document where each process is described more in detail).

Table 4: Current management of the source-separated food waste. In brackets is the number of the section describing each process in this document.

	Source-separated food waste
Barcelona	Anaerobic digestion (3.6) → dewatering (0) → Composting (3.8.7) → use-on-land (3.12.4)
Copenhagen	Anaerobic digestion (3.6) → use-on-land (3.12.4)
Lisbon	Anaerobic digestion (3.6) → dewatering (0) → Composting (3.8.7) → use-on-land
South Wales	Composting (3.8.7) → use-on-land (3.12.4)
Trento	25% to composting (3.8.7) → use-on-land (3.12.4) 75% Anaerobic digestion (3.6) → dewatering (0) → Composting (3.8.7) → use-on-land

Table 5: Current treatment of the non-source-separated food waste (i.e. residual waste). In brackets is the number of the section describing each process in this document.

	Non source-separated food waste (i.e. residual waste)
Barcelona	51% to mechanical biological stabilization (3.13) → landfill (3.13.1) 20% to mechanical biological pre-treatment (3.13) → incineration with energy recovery (3.11.1) 29% to incineration with energy recovery (3.11.1)
Copenhagen	100% to incineration with energy recovery (3.11.1)
Lisbon	18% to anaerobic digestion (3.6) → dewatering (0) → landfill (3.13.1) 44% to landfill (3.13.1) 38% to incineration with energy recovery (3.11.1)
South Wales	100% to incineration with energy recovery (3.11.1)
Trento	28% to mechanical biological pre-treatment (3.13) → incineration with energy recovery (3.11.1) 72% to landfill (3.13.1)

3.4.2 Sewage sludge

The current management of the sewage sludge was based on the total number of wastewater treatment plants present in each cluster: 5 in Barcelona, 3 in Copenhagen, 14 in Lisbon, 3 in South Wales, and 55 in

Trento. Table 6 describes the sewage sludge treatment in 2018 in all the plants present in the different clusters based on the information directly provided by each cluster.

Table 6: Current management (in 2018) of the sewage sludge in all the wastewater treatment plants present in each cluster. In brackets is the number of the section describing each process in this document.

	Number of WWTP	Description of the sewage sludge treatment
Barcelona	5	In 2 WWTPs, the sewage sludge is anaerobically digested (3.6), dewatered (0), and spread on agricultural land (3.12.4). In 1 WWTP, the sewage sludge is anaerobically digested (3.6), dewatered (0), and then 64% is directly spread on agricultural land (3.12.4) and 36% is incinerated (3.11.1). In 2 WWTPs, the sewage sludge is dewatered (0), composted (3.8.7), and spread on agricultural land (3.12.4).
Copenhagen	3	In all the 3 WWTPs, the sewage sludge is anaerobically digested (3.6), dewatered (0), and incinerated (3.11.1).
Lisbon	14	In 2 WWTPs, the sewage sludge is dewatered (0), composted (3.8.7), and spread on agricultural land (3.12.4). In 12 WWTPs, the sewage sludge is anaerobically digested (3.6) and dewatered (0). Of these 5, compost it (3.8.7) before spreading it on agricultural land (3.12.4), 3 spread it directly (3.12.4), and the remaining plants have a different share of dewatered digestate that is composted or directly spread.
South Wales	3	In all the 3 WWTPs, the sewage sludge is anaerobically digested and spread on agricultural land (3.12.4).
Trento	55	In 3 WWTPs (the largest), the sewage sludge is anaerobically digested (3.6), dewatered (0), composted, and spread on agricultural land (3.12.4). In the remaining smaller plants, the sewage sludge is simply dewatered (0), composted, and spread on agricultural land (3.12.4).

3.5 Municipal food waste and sewage sludge composition

3.5.1 Chemical composition

The chemical composition of the municipal food waste (Table 7) and sewage sludge (Table 8: Main references used to calculate the chemical composition of municipal food waste

	Main reference
Barcelona	(Ponsá et al., 2011)
Copenhagen	(Riber et al., 2009a)
Lisbon	(Campuzano and González-Martínez, 2016) and data provided from the cluster
South Wales	Main data provided from the cluster
Trento	(Mattioli et al., 2017)

Table 9) was cluster dependent and was based either on both the information directly provided by each cluster and literature (for food waste) or solely on the information provided by the clusters (for sewage sludge). Table 8 reports the main references used for food waste.

Table 7: Chemical composition of the municipal food waste in the clusters

	Municipal food waste				
	Barcelona	Copenhagen	Lisbon	South Wales	Trento
Water (%)	71	72	69	75	70
TS (%)	29	28	31	25	30
VS (%TS)	77	94	84	92	90
Ash (%TS)	23	6.0	16	7.7	10
C bio (%TS)	45	49	42	47	43
Ca (%TS)	1.4E+00	1.4E+00	1.4E+00	1.5E+00	1.4E+00
Cl (%TS)	8.2E-01	8.2E-01	8.2E-01	8.2E-01	8.2E-01
K (%TS)	1.3E+00	1.1E+00	1.5E+00	1.1E+00	1.2E+00
N (%TS)	1.8E+00	3.1E+00	2.5E+00	3.4E+00	5.0E+00
P (%TS)	4.2E-01	4.1E-01	4.8E-01	3.7E-01	4.2E-01
S (%TS)	3.5E-01	2.3E-01	3.5E-01	4.7E-01	3.5E-01
Al (%TS)	4.7E-02	8.5E-02	4.7E-02	9.7E-03	4.7E-02
As (%TS)	3.6E-05	3.6E-05	3.6E-05	3.6E-05	3.6E-05
Cd (%TS)	6.2E-05	9.9E-06	6.2E-05	1.6E-04	1.9E-05
Co (%TS)	7.9E-04	7.9E-04	7.9E-04	7.9E-04	7.9E-04
Cr (%TS)	7.3E-04	4.3E-04	7.3E-04	4.6E-04	1.3E-03

Cu (%TS)	2.2E-03	1.1E-03	2.2E-03	7.9E-04	4.8E-03
Fe (%TS)	1.8E-02	2.5E-02	1.8E-02	1.2E-02	1.8E-02
Hg (%TS)	2.7E-04	2.0E-06	2.7E-04	7.9E-04	3.0E-05
Mg (%TS)	9.9E-02	1.2E-01	9.9E-02	8.1E-02	9.9E-02
Mn (%TS)	4.9E-03	6.7E-03	4.9E-03	3.1E-03	4.9E-03
Mo (%TS)	1.2E-03	7.4E-05	1.2E-03	2.4E-03	1.2E-03
Ni (%TS)	4.8E-04	2.1E-04	4.8E-04	4.0E-04	8.4E-04
Pb (%TS)	7.4E-04	8.1E-05	7.4E-04	7.9E-04	1.4E-03
Zn (%TS)	7.6E-03	3.1E-03	7.6E-03	2.6E-03	1.7E-02

Table 8: Main references used to calculate the chemical composition of municipal food waste

	Main reference
Barcelona	(Ponsá et al., 2011)
Copenhagen	(Riber et al., 2009a)
Lisbon	(Campuzano and González-Martínez, 2016) and data provided from the cluster
South Wales	Main data provided from the cluster
Trento	(Mattioli et al., 2017)

Table 9: Chemical composition of the sewage sludge in the clusters

	Sewage sludge				
	Barcelona	**Copenhagen**	**Lisbon**	**South Wales**	**Trento**
Water (%)	97	97	97	93	98
TS (%)	3	3.4	3.5	7.5	2.1
VS (%TS)	69	75	77	79	79
Ash (%TS)	31	25	23	21	21
C bio (%TS)	36	36	36	36	36
Ca (%TS)	3.2E+00	3.2E+00	2.8E+00	3.0E+00	3.0E+00
Cl (%TS)	8.9E-01	8.9E-01	8.9E-01	8.9E-01	8.9E-01
K (%TS)	2.8E-01	7.1E-02	1.9E-01	2.1E-01	1.3E+00
N (%TS)	7.3E+00	4.5E+00	5.0E+00	8.9E+00	1.1E+01
P (%TS)	1.7E+00	2.8E+00	2.0E+00	4.3E+00	2.9E+00
S (%TS)	4.5E-01	8.9E-01	4.5E-01	0.0E+00	4.5E-01
Ag (%TS)	1.4E-03	1.4E-03	1.4E-03	1.4E-03	1.4E-03
Al (%TS)	8.7E-01	4.7E-01	6.7E-01	6.7E-01	6.7E-01
As (%TS)	2.5E-04	6.7E-05	4.3E-04	9.5E-04	4.6E-04
B (%TS)	4.7E-03	4.7E-03	4.7E-03	4.7E-03	4.7E-03
Ba (%TS)	2.9E-02	2.9E-02	2.9E-02	2.9E-02	2.9E-02
Cd (%TS)	2.8E-04	3.1E-05	2.0E-04	2.5E-04	1.1E-04
Co (%TS)	5.1E-04	5.1E-04	5.1E-04	5.1E-04	5.1E-04
Cr (%TS)	5.6E-03	2.4E-03	3.7E-03	5.1E-03	2.1E-03
Cu (%TS)	3.3E-02	2.1E-02	1.5E-02	3.3E-02	2.4E-02
Fe (%TS)	1.6E+00	2.9E+00	2.3E+00	2.3E+00	2.3E+00
Hg (%TS)	1.1E-04	6.6E-05	5.3E-05	1.2E-04	1.3E-04
Li (%TS)	2.9E-04	2.9E-04	2.9E-04	2.9E-04	2.9E-04
Mg (%TS)	4.8E-01	4.7E-01	2.9E-01	8.3E-01	5.2E-01
Mn (%TS)	2.3E-02	1.8E-02	2.1E-02	2.1E-02	2.1E-02
Mo (%TS)	6.3E-03	6.1E-04	2.9E-03	1.8E-03	2.9E-03
Ni (%TS)	5.5E-03	2.6E-03	2.1E-03	4.8E-03	1.5E-03
Pb (%TS)	6.2E-03	3.8E-03	3.3E-03	2.0E-02	2.6E-03
Sb (%TS)	6.3E-04	6.3E-04	6.3E-04	6.3E-04	6.3E-04
Se (%TS)	1.1E-04	9.3E-04	5.0E-04	4.6E-04	5.0E-04
Sr (%TS)	7.9E-02	7.9E-02	7.9E-02	7.9E-02	7.9E-02
Ti (%TS)	1.5E-02	1.5E-02	1.5E-02	1.5E-02	1.5E-02
V (%TS)	1.1E-03	1.1E-03	1.1E-03	1.1E-03	1.1E-03
Zn (%TS)	8.8E-02	6.8E-02	6.7E-02	1.2E-01	6.1E-02

3.5.2 Low heating value (LHV)

The low heating value (also called low energy value or low calorific value) describes the heat released during combustion without condensation. The LHV of food waste is usually expressed on wet basis (MJ/ kg wet weight), while the LHV of sewage sludge is typically reported on dry basis (MJ/kg TS). Since we did had have cluster-specific data, we modeled the LHV as a range and we expressed it as MJ/kg VS (Table

10), so the final value would depend on the TS, VS and water content. For information, we report the equation describing how to convert the LHV on dry basis on LHV on wet basis (Hulgaard and Vehlow, 2011):

$$LHV\left[\frac{MJ}{kg\ wet\ weight}\right] = LHV\left[\frac{MJ}{kg\ TS}\right] * \left(1 - \%\ water\left[\frac{kg\ water}{kg\ wet\ weight}\right]\right) - 2.44\left[\frac{MJ}{kg\ water}\right] * \%\ water\left[\frac{kg\ water}{kg\ wet\ weight}\right]$$

Table 10: Low heating value (LHV) expressed in MJ/kg VS for the municipal food waste and sewage sludge. The data were modeled with a triangular uncertainty distribution.

	Mode	Min	Max	Reference
LHV food waste [MJ/kg VS]	22.7	15.7	23.9	Calculated based on (Schaum et al., 2016)
LHV sewage sludge [MJ/kg VS]	20.9	17.8	24.3	Calculated based on (Götze et al., 2016; Hansen et al., 2007a; La Cour Jansen et al., 2004; Riber et al., 2009b)

3.6 Municipal food waste collection

The waste collection was modeled with a diesel collection vehicle, Euro6 driven in urban traffic. Table 11 shows the diesel consumption of the collection of source-separated and non-source-separated food waste (i.e. residual waste) and Table 12 the costs (assumed to be equal to the budget costs) associated with the collection. Both diesel consumption and costs were assumed to be equal in all the clusters.

Table 11: Diesel consumption of a EURO6 vehicle collecting source-separated and non-source-separated (i.e. residual waste) municipal food waste. The diesel consumption was modeled with a triangular uncertainty distribution.

	Unit	Mode	Min	Max	References
Source-separated food waste	l/t	8.1	4.1	12.9	(Gredmaier et al., 2013)
Non-source-separated food waste (i.e. residual waste)	l/t	4.1	1.4	10.1	(Larsen et al., 2009)

Table 12: Budget costs for the collection of source-separated and non-source-separated (i.e. residual waste) municipal food waste. The costs were modeled with a triangular uncertainty distribution.

	Unit	Mode	Min	Max	References
Source-separated food waste	EUR2019/t	146	127	196	(Cunha et al., 2014; D'Onza et al., 2016; Eunomia, 2002a)
Non-source-separated food waste (i.e. residual waste)	EUR2019/t	92	40	210	(Slorach et al., 2019; Tonini et al., 2020; Utilitalia and Bain & Company, 2016)

3.7 Biorefinery producing PHA

The biorefinery analyzed in this study (Figure 31) is a plant that receives source-separated municipal food waste and sewage sludge (in blue in Figure 31) and has as outputs the dried PHA to be sold in the market and the residues (in red in Figure 31). The design was built accordingly to the pilot plant built in Treviso that was the focus of a 3-years project RES URBIS funded by H2020 (Res Urbis, 2019), where the energy efficiencies and the consumptions were upscaled to an industrial scale plant by sketching a full-scale facility and deriving consumptions/costs from process-engineering calculations.

The plant is composed of several steps (as illustrated in Figure 31). First, the source-separated municipal food waste is pre-treated in a similar process as for a wet anaerobic digestion and the residues of the pre-treatment are treated similarly to the rest of the residual waste (cluster dependent and described in section 3.4). Water is then added to the pre-treated food waste to reach the same water content as for a wet digester (see section 3.8.3.1) and food waste is then mixed with sewage sludge. To note that the VS from sewage sludge needs to be a maximum of 25% of the total VS due to the instability observed in the acid fermentation with a higher percentage of VS from sewage sludge. The fermented organic matter is then filtered and sent to two aerobic steps where the PHA is cumulated. Finally, the PHA-rich biomass is centrifuged and the PHA is extracted, dried and ready for the market.

Table 13 and Table 14 show the mass balance and the energy consumption of the different steps of the biorefinery as implemented in the model, while Table 15 specifies the energy and chemical consumption in the PHA extraction.

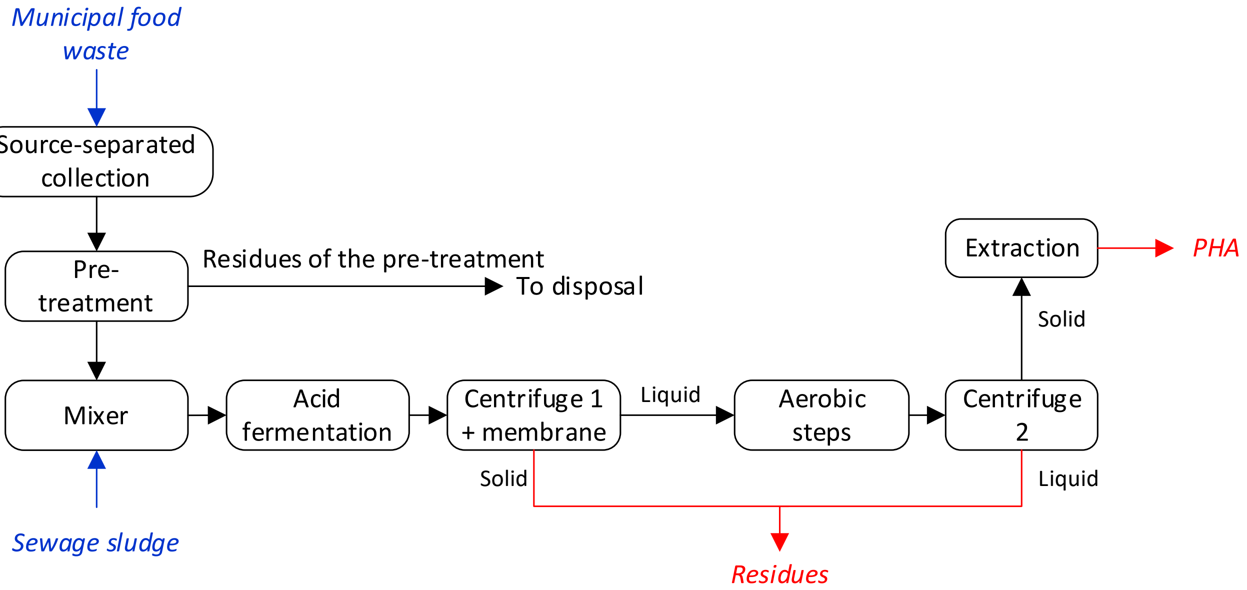

Figure 31: Biorefinery producing PHA, where the inputs of the plant are in blue and the outputs in red.

Table 13: Parameter necessary to calculate the mass balance of the biorefinery. All the parameters were modeled with a triangular uncertainty distribution.

	Unit	Mode	Min	Max
Acid fermentation: VS consumed	% VS entering the acid fermentation	8%	5%	10%
Centrifuge 1 + membrane: transfer coefficient VS to the aerobic steps (used also for C)	% VS entering the centrifuge going to the aerobic steps	31%	30%	35%
Centrifuge 1 + membrane: transfer coefficient ash to the aerobic steps (used also for all the other substances)	% ash entering the centrifuge going to the aerobic steps	7%	5%	10%
Centrifuge 1 + membrane: transfer coefficient water to the aerobic steps	% water entering the centrifuge going to the aerobic steps	72%	70%	75%
Aerobic steps: VS consumed	% VS entering the aerobic steps	46%		
Aerobic steps: transfer coefficient VS to centrifuge 2	% VS entering the aerobic steps (100% of the VS non consumed)	54%		
Aerobic steps: transfer coefficient water to centrifuge 2	% water entering the aerobic steps	15%	10%	20%
Aerobic steps: transfer coefficient ash to centrifuge 2	% ash entering the aerobic steps	0%		
Biorefinery efficiency	kg PHA (before extraction) / kg VS entering the aerobic steps	0.27	0.25	0.3
Extraction efficiency	kg PHA after extraction/kg PHA before extraction	0.90		

Table 14: Energy consumption in the different steps of the biorefinery plant. To notice the very high-energy consumption of the dehydrator in the extraction due to its small size compared to industrial-scale dehydrator. The energy consumption was modeled with a triangular uncertainty distribution of ±20%.

	Unit	Mode
Fermentation	kWh/t input fermentation	4.6
Centrifuge 1 + membrane	kWh/t input centrifuge	5.3
Aerobic steps	kWh/t input aerobic steps	1.4
Centrifuge 2	kWh/t input centrifuge	4.3
Extraction: chemical extraction	kWh/t PHA extracted	20
Extraction: filter press	kWh/t PHA extracted	13
Extraction: dehydrator	kWh/t PHA extracted	1,954

Table 15: Chemical consumption of the PHA extraction modeled with a triangular uncertainty distribution

	Unit	Mode	Min	Max
Sodium hydroxide (NaOH) 50%	kg/kg PHA extracted	0.40	0.28	0.4
Sodium hypochlorite (NaOCl)	kg/kg PHA extracted	0.3	0.3	2
Other inorganic oxidizing agent	kg/kg PHA extracted	0.49	0.25	0.49
Water	kg/kg PHA extracted	40	12	40

3.7.1 Costs

The capital cost of the plant (Table 19) was calculated as the sum of the single components. The uncertainty ranges were based on the different sizes of the plant depending on the cluster, but the uncertainty range was kept constant for all the clusters due to the uncertainty of these numbers. The capital expenditures of the plant and the number of employees illustrated in Table 19 excludes the food waste pre-treatment that was assumed to be equal to the pre-treatment of generic wet anaerobic digestion (described in section 3.8.1). The salary per employee in each cluster is reported in section 3.19 and an additional 20% reserve factor was assumed based on Cimpan et al. (2016a).

The capital expenditures also included the cost of insurance and maintenance (section 3.2) and the operational costs also include the energy (unitary costs described in section 3.17.2) and the ancillary material consumption (unitary costs described in Table 17).

Table 16: capital expenditures (CAPEX) and number of employers of the biorefinery producing PHA calculated per ton of biowaste entering the mixer (sewage sludge plus the pre-treated food waste including the water needed to reach the desired water content) modeled. The CAPEX excludes the pre-treatment of the municipal food waste. The parameters were modeled with a triangular uncertainty distribution.

	Unit	Mode	Min	Max
Annualized CAPEX	EUR2019/t input to the mixer (included the water added to reach the water content of the food waste)	1.78	0.98	2.55
Number of employees	no/t input to the mixer (included the water added to reach the water content of the food waste)	1.37E-05	6.09E-06	1.91E-05

Table 17: Unitary cost of the ancillary material used in the extraction modeled with a triangular uncertainty distribution

	Unit	Mode
Sodium hydroxide (NaOH) 50%	EUR2019/t	244
Sodium hypochlorite (NaOCl)	EUR2019/t	434

3.8 Anaerobic digestion (AD)

The anaerobic digestion (AD) is a technology that transforms organic matter in methane and carbon dioxide in anaerobic conditions (lack of oxygen). AD plants have one main input (i.e. pre-treated source-separated food waste or sewage sludge) and two outputs (biogas and digestate).

The process was modeled equally for source-separated food waste and sewage sludge. There are two main differences between the two substrates. First, food waste needs to be pre-treated to remove impurities and obtain and homogenous substrate, and water has to be added to reach the desired water content (in case of wet digestion). Second, the two substrates are often covered by different legislation regulating the use of the digestate, due to the different level of contaminants: the digestate from food waste is usually spread on land (with or without composting), while the digestate from sewage sludge is either incinerated or spread on land (with or without composting).

3.8.1 Pre-treatment of source-separated municipal food waste

There are several pre-treatments methods for source-separated food waste prior to an AD plant, as pulping, screw press, and disc screen (Khoshnevisan et al., 2018). We assumed that the pre-treatment of food waste in all the clusters was hydropulping since it is one of the most common food waste pre-treatment technology in Europe (Banks et al., 2018). Hydropulping includes several units (e.g. a pulper, a separator, a dewatering unit and a reject washing unit (Khoshnevisan et al., 2018). Table 18 shows the water and the electricity consumption and the overall separation efficiency ($\frac{kg\ food\ waste\ output}{kg\ food\ waste\ input}$) of similar pulping technologies. However, it was not possible to find the electricity consumption of AD plants excluding the pre-treatment technologies and the majority of sources only reported aggregated values. For this reason, the electricity consumption of the pre-treatment was included in the overall electricity consumption of the anaerobic digestion plant (see section 3.8.4). To note that the separation efficiency for other technologies as the screw press and the disc screen can be lower than 70% (Hansen et al., 2007b).

*Table 18: Electricity consumption, water consumption, and separation efficiency of the pulping technology used as a pre-treatment of the source-separated food waste. All the parameters were modeled with a triangular uncertainty distribution. *the electricity consumption of the pre-treatment was included in the overall energy consumption of the AD plant described in section 3.8.4.*

	Unit	Mode	Min	Max	Reference
Electricity consumption reported only for pulping*	kWh/t food waste with impurities	34.2	26.5	41.0	(Bozano Gandolfi, 2012; ETV, 2015; Khoshnevisan et al., 2018; Naroznova et al., 2016a)
	kWh/ t food waste without impurities	39.0	30.2	46.7	
Water consumption	kg clean water/ t food waste with impurities	763	400	1,210	(ETV, 2015; Khoshnevisan et al., 2018; Naroznova et al., 2016a)
	kg clean water/ t food waste without impurities	869	456	1,379	
Separation efficiency	%	90%	80%	97%	(Bernstad and la Cour Jansen, 2011; ETV, 2015)

3.8.2 Methane generation rate

3.8.2.1 Source-separated food waste

There are several types of anaerobic digestion plants in the world with very different technical properties. We modeled a generic mesophilic wet plant with an average temperature of 35 degrees (Angelidaki and Batstone, 2011). The bio-methane production of source-separated food waste was modeled with a triangular uncertainty distribution, where the mode (Table 19) was cluster-dependant and the minimum (252 m^3 CH_4/t VS) and the maximum (580 m^3 CH_4/t VS) were assumed the same in all the clusters and were based on a broader literature review. In case the literature reported only the Biochemical Methane Potential (BMP), we corrected the value assuming that the specific methane production was 75% of the BMP (Banks et al., 2018; Møller et al., 2011).

Table 19: Methane production of the anaerobic digestion of source-separated food waste in m^3 of CH_4/t VS. All the parameters were modeled with a triangular uncertainty distribution.

Cluster	Unit	Value	Reference
Mode for the cluster of Barcelona	m^3 CH_4/t VS	366	Internal communication
Mode for the cluster of Copenhagen	m^3 CH_4/t VS	337	(Davidsson et al., 2007)
Mode for the cluster of Lisbon	m^3 CH_4/t VS	357	Average of the other clusters
Mode for the cluster of South Wales	m^3 CH_4/t VS	424	(Banks et al., 2011; Zhang et al., 2012)
Mode for the cluster of Trento	m^3 CH_4/t VS	300	Northern Italian data from Campuzano and González-Martínez (2016)
Min for all clusters	m^3 CH_4/t VS	252	Minimum of 54 values (Banks et al., 2018; Browne and Murphy, 2013; Campuzano and González-Martínez, 2016; Davidsson et al., 2007; Møller et al., 2011; Naroznova et al., 2016b)
Max for all clusters	m^3 CH_4/t VS	580	Maximum of 54 values (Banks et al., 2018; Browne and Murphy, 2013; Campuzano and González-Martínez, 2016; Davidsson et al., 2007; Møller et al., 2011; Naroznova et al., 2016b)

In the cluster of Lisbon, a part of the non-source-separated food waste is sent to a mechanical biological plant (section 3.4.1) and the fine fraction is treated in an anaerobic digestion plant before being composted and landfilled. In this case, the methane production was based on the residual waste studied in Zhang et al. (2012) and was modeled with a triangular distribution having the mode equal to 331 m^3 CH_4/t VS, the minimum to 262 m^3 CH_4/t VS and the maximum to 418 m^3 CH_4/t VS.

3.8.2.2 Sewage sludge

On the contrary to food waste, sewage sludge does not need any additional pre-treatment. Table 20 shows the methane production in m^3 CH_4 per ton of VS entering the digester based on the specific information collected from each cluster. The mode of the current anaerobic digestion of the sewage sludge was calculated as the ratio between the sum of the bio-methane generated in all the plants of the cluster and the sum of the VS entering all the digesters in the cluster. The minimum and maximum methane production were identified as the lowest and highest value found in the cluster.

*Table 20: Methane production of the anaerobic digestion of sewage sludge in m^3 of CH_4/t VS based on the data provided from each cluster. *Trento was the only case that did not provide specific information and for this reason, we used the median, the minimum and maximum value of all the other plants. All the parameters were modeled with a triangular uncertainty distribution.*

	Unit	Mode	Min	Max
Barcelona	m^3 CH_4 / t VS input	305	267	317
Copenhagen	m^3 CH_4 / t VS input	262	248	269
Lisbon	m^3 CH_4 / t VS input	242	74	312
South Wales	m^3 CH_4 / t VS input	238	197	319
Trento*	m^3 CH_4 / t VS input	255	74	345

3.8.2.3 Biorefinery residues

The methane production from the digestion of the biorefinery residues was modeled as being 90% of the m^3 CH_4 per t VS without the biorefinery based on the information collected in the pilot-plant working in Treviso. The total methane production of the biorefinery residues was modeled as the sum of the methane that is generated from the food waste (90% of the values reported in Table 19) and the methane that is generated from the sewage sludge (90% of the values reported in Table 20), even if the two substrates are in reality mixed.

3.8.3 Mass balance

This section describes all the additional information used to model the AD plants: the transfer coefficients of the input VS, ash, and water to the digestate and the transfer coefficient of C to the biogas and to the digestate. All the other elements (e.g. nutrients and heavy metals) entering the plant, were assumed to remain in the digestate (Møller et al., 2011).

The methane content of the biogas was assumed to be the same in all cases and was modeled with a triangular uncertainty distribution between 57% and 64%, with a mode equal to 64% (Angelidaki and Batstone, 2011; Banks et al., 2011; Bernstad and la Cour Jansen, 2011; Browne and Murphy, 2013; Møller et al., 2011).

3.8.3.1 Food waste

Table 21 summarizes all the information used to model the AD plant treating food waste (both source-separated and from residual waste after MBT).

Table 21: Characteristics of the mesophilic wet anaerobic digester treating municipal food waste. All the parameters were modeled with a triangular uncertainty distribution.

	Unit	Mode	Min	Max	Reference
Water content in the AD plant	%	90%	88%	91%	(Angelidaki and Batstone, 2011; Banks et al., 2018, 2011; Cecchi et al., 2011; Greenfinch Ltd, 2010)
Transfer coefficient: VS to digestate	% input VS	14%	5%	38%	(Ardolino et al., 2018; Banks et al., 2018, 2011; Bernstad and la Cour Jansen, 2011; Cecchi et al., 2011; Greenfinch Ltd, 2010)
Transfer coefficient: water to digestate	% input water	95%	94%	99%	(Banks et al., 2018, 2011; Greenfinch Ltd, 2010)
Transfer coefficient: ash to digestate	% input ash	100%			
Transfer coefficient: C to digestate	% input C	25%	18%	46%	Mode from Møller et al. (2011). Uncertainty assumed the same as the VS

3.8.3.2 Sewage sludge

The transfer coefficients of the input VS, ash and, water to the digestate in the scenario alternatives modeling the counter-factual of sewage sludge with the current management ("FW_sep.", "FW_residual", "FW_AD", "FW_Inc") were cluster-dependant and based on the specific information collected from each cluster. Table 22 shows the VS degradation in each cluster.

Table 22: VS degradation of the anaerobic digestion plants treating sewage sludge of the scenario alternatives modeling the counter-factual of sewage sludge with the current management ("FW_sep.", "FW_residual", "FW_AD", "FW_Inc").

	Unit	Mode
Barcelona	% VS input	63%
Copenhagen	% VS input	47%
Lisbon	% VS input	53%
South Wales	% VS input	40%
Trento	% VS input	60%

The VS degradation in all the other scenario alternatives ("SS_AD_Inc" and "SS_AD_UOL") was assumed to be the same independently from the cluster (Table 23). Furthermore, the transfer coefficients of ash, water, and C were modeled as constant based on Yoshida et al. (2018) and are reported in Table 23. The higher transfer coefficients of VS to digestate in the case of sewage sludge compared to food waste (and the respective lower VS degradation rate) indicates that food waste is more easily digestible than sewage sludge.

Table 23: Generic characteristics of the mesophilic wet anaerobic digester of sewage sludge. All the parameters were modeled with a triangular uncertainty distribution.

	Unit	Mode	Min	Max	Reference
Transfer coefficient: VS to digestate	% input VS	60%	42%	71%	Yoshida et al. (2018) and information collected from the plants built in the clusters
Transfer coefficient: water to digestate	% input water	98%			(Yoshida et al., 2018)
Transfer coefficient: ash to digestate	% input ash	100%			(Yoshida et al., 2018)
Transfer coefficient: C to digestate	% input C	36%			(Yoshida et al., 2018)

3.8.3.3 Biorefinery residues

The mass balance of the AD plant treating the biorefinery residues was modeled as a theoretical sum of an AD plant treating only the food waste part of the residues (described in Table 21) and an AD plant treating only the sewage sludge (described in Table 23), even if food waste and sewage sludge are in reality mixed.

3.8.4 Diesel and energy consumption

Table 24 shows the diesel and energy consumption of the anaerobic digester plant (including pre-treatment in case of food waste). The diesel was modeled as combusted in a 94 kW wheel loader.

The heat consumption is assumed to be covered 100% by the internal biogas generation when the biogas is combusted in a CHP engine (described in section 3.8.6.1).

The heat consumption of the AD plants treating sewage sludge was modeled as the heat needed to raise the temperature of the water and of the TS to the desired 35° (for the mesophilic plants) due to the lack of data:

$$Heat\ consumption\ [MJ] = kg\ TS\ input * 0.003\frac{MJ}{kg\ TS*°C} * (35° - average\ T\ in\ the\ cluster) + kg\ water\ input * 0.0042\frac{MJ}{kg\ water*°C} * (35° - average\ T\ in\ the\ cluster),$$

The average temperatures (T in the above formula) in the clusters were assumed to be 17° in Barcelona, 8.4° in Copenhagen, 17° in Lisbon, 10° in South Wales, and 13° in Trento (Climate-Data.org, 2020).

*Table 24: Energy and diesel consumption of the AD plants. The electricity consumption of food waste includes the pre-treatment. The heat consumption is assumed to be covered 100% by the internal biogas generation when the biogas is combusted in a CHP engine. *Min and max calculated based on the uncertainty of the electricity consumption of food waste. ** Min and max calculated based on the uncertainty of the diesel consumption of food waste. All the parameters were modeled with a triangular uncertainty distribution.*

	Unit	Mode	Min	Max	Reference
Electricity consumption (food waste)	kWh / t food waste before pre-treatment	50	8	101	(Ardolino et al., 2018; Banks et al., 2011; Greenfinch Ltd, 2010; Jungbluth et al., 2007; Møller et al., 2011)
Heat consumption (food waste)	MJ / t food waste before pre-treatment	363	61	594	(Ardolino et al., 2018; Banks et al., 2011; Jungbluth et al., 2007)
Electricity consumption (sewage sludge)*	kWh / t TS	70	12	142	(Yoshida et al., 2018)
Diesel consumption (all substrates)**	l / t wet weight input to the digester	0.90	0.15	1.8	(Møller et al., 2011)

3.8.5 Methane leakage

Methane leakage indicates the percentage of methane that is emitted during the anaerobic digestion of organic material. Two main methods exist to quantify the methane emissions: the remote sensing method and the on-site measurements. The remote sensing method measures the average concentration of the entire site, it gives more complete information but it is not possible to extrapolate the source of the emissions (e.g. engine, leakages in the pipes). On the contrary, the on-site measurements are able to individuate individual leakages for repair but can result in an underestimation of the emissions (Jørgensen and Kvist, 2015). Methane can leak from different parts of the system (Liebetrau et al., 2017): storage, digestion process, open digestate storage tank, post composting. In literature the emissions vary dramatically depending on the type of cover (robber or concrete), the handling of the aeration of the digestate (gas-tight, covered or open), the use of the pressure relief valves, etc. (Daniel-Gromke et al., 2015; Hrad et al., 2015; Liebetrau et al., 2017). Normally the largest emissions sources are the digestate storage tanks (if open) and the pressure release valves (Reinelt et al., 2017).

Even if Scheutz and Fredenslund (2019) noticed that the methane emissions seems to be higher in plants treating sewage sludge compared to other types of organic waste, we assumed that the methane leakage was the same in the anaerobic digestion of all studied organic waste (source-separated food waste, non-source-separated food waste, sewage sludge, biorefinery residues).

We modeled three different sources of methane leakage: the digester, the biogas utilization (either in a CHP or in an upgrading plant) and the digestate storage tank. Table 25 shows the methane leakage for each generation source with the following clarifications:

- We assumed that the methane emission from the feeding system was negligible (Liebetrau et al., 2017).
- We assumed that the digestate tank was not open air. In this latter case, the methane emissions could be above 10% of the generated biogas (Liebetrau et al., 2013).

Table 25: Methane leakage per source. All the parameters were modeled with a triangular uncertainty distribution.

Source	Unit	Mode	Min	Max	Reference
Digester	% generated CH_4	1.5%	0%	5.7%	(Bernstad and la Cour Jansen, 2011; Jørgensen and Kvist, 2015; Reinelt et al., 2017; UNFCCC/CCNUCC, 2012)
Digestate storage tank	% generated CH_4	1.9%	0.22%	3.5%	(Liebetrau et al., 2013; Reinelt et al., 2017)
CHP plant	% CH_4 entering the CHP plant	1.8%	0.4%	4.4%	(Hansen et al., 2015; Liebetrau et al., 2017, 2013; Nielsen et al., 2010)
Biogas upgrading with a water scrubber	% CH_4 entering the water scrubber	1.0%	0.1%	2.0%	(Bauer et al., 2013; Liebetrau et al., 2017, 2013)

All the methane leakage was minimized in the framework scenario c) (Table 26): all the leakages from the digester were repaired, the emissions from the CHP respected the proposed legislation in Netherlands and Germany and the digestate was stored in a gas-tight closed environment. To be noted that Energinet

(2020) forecasts that a total of 2% methane leakage is a realistic average for existing plants (including the biogas utilization), while Danish industries aim at reaching 1% (Energinet, 2019).

Table 26: Methane leakage in the framework scenario c) where all the methane emissions were minimized. All the parameters were modeled with a triangular uncertainty distribution.

Source	Unit	Mode	Min	Max	Reference
Digester	% generated CH_4	0.24%	0%	1.2%	(Jørgensen and Kvist, 2015; Liebetrau et al., 2013)
Digestate storage tank	% generated CH_4	0%			Assumed gas-tight digestate storage tank where the emissions can be 0% (Liebetrau et al., 2013)
CHP plant	% CH_4 entering the CHP plant	0.17%	0.15%	0.19%	Proposed legislation in Netherlands and Germany (Liebetrau et al., 2017)

3.8.6 Biogas utilization

The generated biogas can be used for energy production or upgraded for vehicle fuel production (minimum 95% methane content) or for injection in the natural gas grid (above 99%) (Jansen, 2011).

In the baseline alternatives, we assumed that the biogas was treated to reduce water and sulfur content and was combusted for energy production (section 3.8.6.1): all the internal energy consumption was covered with the internal biogas production, and all the surplus electricity was sold to the grid.

In the framework scenario d), the biogas was upgraded through water scrubbing and injected in the natural gas transmission grid at 40 bars (section 3.8.6.2).

3.8.6.1 Combined heat and power plant (CHP)

Combined heat and power (CHP) plants transform the energy in the biogas into electricity and heat. Table 27 shows the gross electrical and heat efficiency of the biogas CHP plant, and 4% of the generated electricity and 22% of the generated heat was lost as parasitic electricity and heat waste (Banks et al., 2011). Furthermore, we assumed that the internal electricity consumption was covered from the electricity generation and the remaining was sold to the grid (i.e. and avoids marginal electricity). Since the majority of AD plants are placed outside the urban centers and are not connected to district heating, the generated heat is not sold to the grid. The heat is used to cover the internal consumption, a part of the wastewater treatment plants' need (in case of anaerobic digestion of sewage sludge) or dissipated to the atmosphere.

Table 27: Gross electrical and heat efficiency for the biogas combined heat and power plant

	Mode	Min	Max	References
Gross electrical efficiency	35%	21%	43%	(Ardolino et al., 2018; Banks et al., 2011; Greenfinch Ltd, 2010; Mergner et al., 2012; Møller et al., 2011; Yoshida et al., 2015)
Gross heat efficiency	45%	35%	53%	(Ardolino et al., 2018; Banks et al., 2011; Greenfinch Ltd, 2010; Mergner et al., 2012; Møller et al., 2011)

Table 28 shows the direct emissions of the biogas combustion engine based on Nielsen et al. (2010) and Kristensen et al. (2004).

*Table 28. Direct emissions to air of the biogas combustion engine from Nielsen et al. (2010) and Kristensen et al. (2004). The methane emissions are reported in section 3.8.5. All the parameters were modeled with a triangular uncertainty distribution. *calculated based on the minimum and maximum uncertainty of the emissions that were reported with an uncertainty.*

	Average	MIN	MAX
	kg/MJ	kg/MJ	kg/MJ
NOx	3.05E-04	1.09E-04	5.40E-04
Non-methane volatile organic compound (NMVOC)	1.13E-05	3.00E-06	1.80E-05
CO	2.67E-04	5.10E-05	4.32E-04
N2O	1.43E-06	5.00E-07	2.10E-06
Arsenic (As)*	4.00E-11	6.48E-12	1.47E-10
Cadmium (Cd)*	2.00E-12	3.24E-13	7.33E-12
Cobalt (Co)*	2.10E-10	3.40E-11	7.70E-10
Chromium (Cr)*	1.80E-10	2.92E-11	6.60E-10
Cupper (Cu)*	3.10E-10	5.03E-11	1.14E-09
Mercury (Hg)*	1.20E-10	1.95E-11	4.40E-10
Manganese (Mn)*	1.90E-10	3.08E-11	6.97E-10
Nickel (Ni)*	2.30E-10	3.73E-11	8.43E-10
Lead (Pb)*	5.00E-12	8.11E-13	1.83E-11
Antimony (Sb)*	1.20E-10	1.95E-11	4.40E-10
Selenium (Se)*	2.10E-10	3.40E-11	7.70E-10
Thallium (Tl)*	2.10E-10	3.40E-11	7.70E-10
Vanadium (V)*	4.00E-11	6.48E-12	1.47E-10
Zinc (Zn)*	3.95E-09	6.40E-10	1.45E-08
Poly Chlorinated Dibenzo Dioxins and Furans (PCDD/-F)*	9.60E-16	1.56E-16	3.52E-15
Benzo[a]pyrene (BaP)*	4.20E-12	6.81E-13	1.54E-11
Sum PAH	3.05E-10	3.00E-12	6.06E-10
Naphthalene	3.94E-09	3.30E-09	4.58E-09
Hexachlorobenzene (HCB)*	1.90E-13	3.08E-14	6.97E-13
Formaldehyde	1.41E-05	6.40E-06	2.12E-05
Acetaldehyde	1.83E-07	5.10E-08	4.53E-07
Acrolein	5.50E-09	1.00E-09	1.00E-08
Propanal	4.37E-08	1.00E-09	1.07E-07
Acetone	3.28E-08	9.00E-09	7.90E-08
Benzaldehyde	1.18E-08	0.00E+00	2.80E-08
PM10	2.26E-07	1.79E-09	4.51E-07
PM25	1.05E-07	3.13E-09	2.06E-07

3.8.6.2 Biogas upgrading (for the framework scenario)

The biogas upgrading was modeled with the technology water scrubbing (Energinet, 2019). Efficiency, water, and electricity consumption are summarized in Table 29.

Table 29: Energy consumption and efficiency of upgrading biogas with a water scrubber. The methane slip is reported in section 3.8.5. All the parameters were modeled with a triangular uncertainty distribution.

	Unit	Mode	Min	Max	Reference
Efficiency	% (m^3 methane output/m^3 methane input)	98.5%			Bauer et al., 2013; Energinet, 2019)
Water consumption	m^3/Nm^3 biogas	2.2E-3	4.0E-4	4.0E-3	Bauer et al., 2013; Energinet, 2019)
Electricity consumption (upgrading)	kWh/Nm^3 biogas	0.26	0.13	0.30	(Bauer et al., 2013; Energinet, 2019)
Electricity consumption (compression to 40bars to be injected in the natural gas transmission network)	kWh/Nm^3 biogas	0.06	0.03	0.07	The mode is based on Bauer et al. (2013). The uncertainty range is calculated based on the uncertainty of the electricity consumption during upgrading

3.8.7 Costs of food waste pre-treatment, AD plants, and biogas utilization

The budget costs included the annualized CAPEX of the food waste pre-treatment (Table 30), of the AD plant (Table 30), and of the biogas utilization (Table 30), the insurance and maintenance of the CAPEX (calculated as a percentage of the CAPEX as described in section 3.2), the energy and diesel consumption (unitary costs described in section 3.17.2), and the cost of the employees (unitary costs described in section 3.19) assuming an additional 20% reserve factor based on Cimpan et al. (2016a).

*Table 30: Capital expenditures (CAPEX) and number of employees of the food waste pre-treatment (prior of the AD plant), of the AD plant, and of the biogas utilization (both combustion and upgrading to bio-methane). *it includes the weight of the water added to reach the desired water content. CHP: Combined heat and power plant.*

	Unit	Mode	Min	Max	Reference
Annualized CAPEX of the food waste pre-treatment	EUR2019/t food waste before pre-treatment	2.1	1.8	2.5	(Danish Energy Agency, 2020) and costs of the designed pre-treatment for the PHA biorefinery
Annualized CAPEX of the AD plant	EUR2019/t food waste after pre-treatment*	4.1	2.3	8.3	(COWI, 2004; Danish Energy Agency, 2020; Energinet, 2019; Martinez-Sanchez et al., 2015) and data provided by the analyzed clusters
Number of employees of the AD plant	no/t food waste after pre-treatment*	7.3E-05	2.9E-05	2.5E-04	(COWI, 2004; Danish Energy Agency, 2020; Energinet, 2019; Martinez-Sanchez et al., 2015) and data provided by the analyzed clusters
Annualized CAPEX of the biogas CHP plant	EUR2019/m^3 CH_4 input	0.028	0.020	0.037	(Danish Energy Agency, 2020; Energinet, 2020)
Annualized CAPEX of the biogas upgrading	EUR2019/m^3 CH_4 input	0.040	0.025	0.048	(Danish Energy Agency, 2020; Energinet, 2019)

3.9 Composting

Composting is an aerobic process that was modeled for different substrates (food waste, sewage sludge or biorefinery residues) and with or without anaerobic digestion. The modeled technology was vessel composting, where the air emissions were treated in a biofilter before being released into the atmosphere. Table 31 summarizes the data used in the modeling.

Table 31: Characteristics of the vessel composting of food waste, sewage sludge, and biorefinery residues. All the parameters were modeled with a triangular uncertainty distribution.

	Unit	Mode	Min	Max	Reference
Electricity consumption	kWh/t input	37	48	56	(Boldrin et al., 2009)
VS degradation	% VS input	59%	44%	79%	(Bernstad and la Cour Jansen, 2011; Boldrin et al., 2009)
C degradation	% C input	59%	44%	79%	Assumed the same as the VS degradation rate (as in Boldrin et al. (2009))
N degradation	% N input	69%	67%	71%	(Bernstad and la Cour Jansen, 2011; Boldrin et al., 2009)
Emissions CH_4_C (before bio-filter)	% C degraded	0.5%	0.011%	5.6%	(Bernstad and la Cour Jansen, 2011; Boldrin et al., 2011, 2009; Pipatti et al., 2006; Sánchez et al., 2015)
Emissions NH_3_N (before bio-filter)	% N degraded	95%	83%	96%	(Bernstad and la Cour Jansen, 2011; Boldrin et al., 2011)
Emissions N_2O_N (before bio-filter)	% N degraded	0.5%	0.0073%	3.7%	(Bernstad and la Cour Jansen, 2011; Boldrin et al., 2011; Pipatti et al., 2006; Sánchez et al., 2015)
Biofilter efficiency for CH_4	% CH_4 emitted	95%	95%	99%	Mode from Boldrin et al. (2009); uncertainty assumed equal to the uncertainty of the bio-filter efficiency for NH_3
Biofilter efficiency for NH_3	% NH_3 emitted	95%	95%	99%	(Boldrin et al., 2009; Frederickson et al., 2013)
Biofilter efficiency for N_2O	% N_2O emitted	0%			(Boldrin et al., 2009)
Water content compost (food waste)	% wet weight	64%	77%	68%	(Boldrin et al., 2011)
Water content compost (sewage sludge)	% wet weight	29%	35%	35%	(Cunha-Queda et al., 2010; Kosobucki et al., 2000)

The budget costs included the CAPEX (Table 32), the cost of maintenance and insurance (calculated as a percentage of the CAPEX (described in section 3.2), the cost of the employees (number in Table 32 and unitary costs in section 3.19), and the energy consumption (unitary costs in 3.14.1). A 20% reserve factor was assumed based on Cimpan et al. (2016a).

Table 32: Annualized capital expenditures (CAPEX) and number of employees of the composting process.

	Unit	Mode	Min	Max	Reference
Annualized CAPEX	EUR2019/t	22	4	53	(COWI, 2004; EPEM SA, 2011; Eunomia, 2002a)
Number of employees	no/t	2.4E-04	1.3E-04	3.5E-04	(Eunomia, 2002a)

3.10 Dewatering of the digestate

The dewatering process aims at reducing the water content of raw sewage sludge or digestate and generates two outputs: a solid fraction and a liquid fraction (called reject water). The most common technologies for solid-liquid separation are screw presses and centrifuges (Drosg et al., 2015). Table 41 shows the consumption of electricity and coagulant and the transfer coefficients to the solid fraction of the modeled generic dewatering process based on the literature available especially for manure. We assumed that the dewatering was always present before incineration or composting.

*Table 33: Electricity consumption, coagulant consumption, and transfer coefficients to the solid fraction of the modeled generic dewatering process. *the uncertainty was calculated based on the uncertainty of the ash, manually constraining the maximum to 100%. All the parameters were modeled with a triangular uncertainty distribution.*

	Unit	Mode	Min	Max	Reference
Electricity	kWh/kg TS	2.29E-02	8.97E-04	5.63E-02	(Jungbluth et al., 2007; Møller et al., 2000; Yoshida et al., 2018) and mass balance of the WWTPs in the clusters
Coagulant (acrylonitrile)	kg / kg TS	9.27E-03	3.70E-03	2.02E-02	(Jungbluth et al., 2007; Yoshida et al., 2018) and mass balance of the WWTPs in the clusters
Water content of the solid fraction	% water input	71%	63%	81%	(Drosg et al., 2015; Møller et al., 2002, 2000; Yoshida et al., 2018) and mass balance of the WWTPs in the clusters. However, the water content of the solid fraction was modeled
TC VS	% VS input	70%	54%	96%	(Bauer et al., 2009; Drosg et al., 2015; Yoshida et al., 2018) and mass balance of the WWTPs in the clusters
TC ash	% ash input	57%	29%	88%	(Bauer et al., 2009; Drosg et al., 2015; Yoshida et al., 2018) and mass balance of the WWTPs in the clusters
TC N	% N input	48%	13%	89%	(Bauer et al., 2009; Drosg et al., 2015; Møller et al., 2007, 2002, 2000; Yoshida et al., 2018)
TC P	% P input	40%	17%	91%	(Bauer et al., 2009; Drosg et al., 2015; Møller et al., 2007, 2002, 2000; Yoshida et al., 2018)
TC K	% K input	20%	3.9%	69%	(Bauer et al., 2009; Drosg et al., 2015; Møller et al., 2007; Yoshida et al., 2018)
TC C	% C input	71%	60%	91%	(Bauer et al., 2009; Drosg et al., 2015; Yoshida et al., 2018)
TC Mg	% Mg input	85%	79%	88%	(Møller et al., 2007; Yoshida et al., 2018)
TC Cu	% Cu input	92%	88%	96%	(Møller et al., 2007; Yoshida et al., 2018)
TC Ag*	% Ag input	97%	50%	100%	(Yoshida et al., 2018)
TC Al*	% Al input	97%	50%	100%	(Yoshida et al., 2018)
TC As*	% As input	96%	49%	100%	(Yoshida et al., 2018)
TC B*	% B input	92%	47%	100%	(Yoshida et al., 2018)
TC Ba*	% Ba input	92%	47%	100%	(Yoshida et al., 2018)
TC Ca*	% Ca input	85%	43%	100%	(Yoshida et al., 2018)
TC Cd*	% Cd input	90%	46%	100%	(Yoshida et al., 2018)
TC Cl*	% Cl input	5.5%	2.8%	8.4%	(Yoshida et al., 2018)
TC Co*	% Co input	89%	46%	100%	(Yoshida et al., 2018)
TC Cr*	% Cr input	90%	46%	100%	(Yoshida et al., 2018)
TC Fe*	% Fe input	93%	48%	100%	(Yoshida et al., 2018)
TC Hg*	% Hg input	82%	42%	100%	(Yoshida et al., 2018)

TC Li*	% Li input	71%	36%	100%	(Yoshida et al., 2018)
TC Mn*	% Mn input	91%	47%	100%	(Yoshida et al., 2018)
TC Mo*	% Mo input	58%	30%	89%	(Yoshida et al., 2018)
TC Ni*	% Ni input	89%	46%	100%	(Yoshida et al., 2018)
TC Pb*	% Pb input	92%	47%	100%	(Yoshida et al., 2018)
TC S*	% S input	94%	48%	100%	(Yoshida et al., 2018)
TC Sb*	% Sb input	80%	41%	100%	(Yoshida et al., 2018)
TC Se*	% Se input	96%	49%	100%	(Yoshida et al., 2018)
TC Sr*	% Sr input	99%	51%	100%	(Yoshida et al., 2018)
TC Ti*	% Ti input	66%	34%	100%	(Yoshida et al., 2018)
TC Zn*	% Zn input	90%	46%	100%	(Yoshida et al., 2018)
TC V*	% V input	77%	40%	100%	(Yoshida et al., 2018)

However, the transfer coefficients to the solid fraction of VS, ash, and water of the sewage sludge dewatering in the alternative scenarios modeling the counter-factual of sewage sludge with the current management ("FW_sep.", "FW_residual", "FW_AD", "FW_Inc") were calculated based on the data directly collected from the wastewater treatment plants in the cluster (Table 34).

Table 34: Transfer coefficients of VS, ash, and water to the solid fraction of the dewatering unit in the alternative scenarios modeling the counter-factual of sewage sludge with the current management ("FW_sep.", "FW_residual", "FW_AD", "FW_Inc"). All the parameters were modeled with a triangular uncertainty distribution.

	VS	Ash	Water
Barcelona	82%	75%	6.2%
Copenhagen	80%	75%	3.8%
Lisbon	78%	61%	6.1%
South Wales	95%	85%	11%
Trento	82%	75%	5.7%

3.10.1 Costs

The budget costs included the CAPEX (Table 37), the insurance and maintenance costs (calculated as a percentage of the CAPEX as described in section 3.2), the energy consumption (unitary costs in 3.14.1), and the coagulant consumption (unitary cost in Table 37).

*Table 35: Annualized capital expenditures (CAPEX) of the dewatering calculated assuming 8 hours per day and 210 working hours per year. The two technologies considered were a screw extractor and a rotary screen. *Assumed a 20% uncertainty. Both the data were modeled with a triangular uncertainty distribution.*

	Unit	Mode	Min	Max	Reference
Annualized CAPEX	EUR2019/t	0.20	0.11	0.30	(Bauer et al., 2009)
Coagulant (acrylonitrile)	EUR2019/t	911*			ecoinvent 3.6

3.11 Treatment of the reject water from the dewatering

The reject water from the dewatering unit was assumed to be sent to a wastewater treatment plant independently from the substrate (food waste, sewage sludge, biorefinery residues). The effluent from the wastewater treatment plant was marine water in Barcelona, Copenhagen, Lisbon, and South Wales (based on the geographical location of the plants), and was surface water in Trento. Table 36 shows the energy and chemicals consumption and Table 37 the transfer coefficients to air and water. All the substances that are neither emitted to air or discharged in the effluent end up in the sludge (incinerated if the sludge is incinerated and used on agricultural land if the sludge is used as fertilizer).

*Table 36: Energy and chemicals consumption of the wastewater treatment plant treating the reject water from the dewatering unit. *Min and max calculated based on the uncertainty of the electricity. **Min and max calculated based on the uncertainty of $FeCl_3$. All the parameters were modeled with a triangular uncertainty distribution.*

Source	Unit	Mode	Min	Max	Reference
Electricity consumption	kWh/t wet weight	0.28	0.17	0.44	(Doka, 2009; Yoshida et al., 2018)
Heat consumption*	MJ/t wet weight	0.033	0.02	0.052	(Doka, 2009)
Iron (III) chloride ($FeCl_3$)	kg/kg P removed	8.5	7.5	10	(Doka, 2009; Yoshida et al., 2018)

Iron sulfate ($FeSO_4$)**	kg/kg P removed	7.5	6.6	9.0	(Doka, 2009)
Aluminum sulfate ($Al_2(SO_4)_3$)**	kg/kg P removed	2.0	1.8	2.4	(Doka, 2009)

Table 37: Transfer coefficients of the wastewater treatment plant treating the reject water from the dewatering unit. All the parameters were modeled with a triangular uncertainty distribution.

	Unit	Mode	Min	Max	Reference
Transfer coefficient to air (equal to emissions to air)					
VS	% VS input	12%	10%	13%	(Yoshida et al., 2018). Uncertainty calculated on the uncertainty of C
CO_2_C	% C input	27%	25%	30%	(Yoshida et al., 2018)
N	% N input	58%	52%	64%	(Yoshida et al., 2018). Uncertainty calculated on the uncertainty of C
N_2O_N	% N input	1.8%	0.016%	4.5%	(Bartram et al., 2019; Yoshida et al., 2018)
Transfer coefficient to the effluent (equal to emissions to water)					
Water	% water input	99%	97%	100%	(Yoshida et al., 2018)
VS	% VS input	37%	37%	38%	(Yoshida et al., 2018)
Ash	% ash input	92%	90%	93%	(Yoshida et al., 2018)
Ag	% Ag input	45%	9.2%	97%	(Yoshida et al., 2018)
Al	% Al input	2.7%	0.30%	5.0%	(Yoshida et al., 2018)
As	% As input	56%	41%	78%	(Yoshida et al., 2018)
B	% B input	31%	13%	50%	(Yoshida et al., 2018)
Ba	% Ba input	9.0%	5.0%	13%	(Yoshida et al., 2018)
C	% C input	21%	21%	21%	(Yoshida et al., 2018)
Ca	% Ca input	91%	90%	93%	(Yoshida et al., 2018)
Cd	% Cd input	30%	13%	50%	(Yoshida et al., 2018)
Cl	% Cl input	100%	99%	100%	(Yoshida et al., 2018)
Co	% Co input	38%	25%	50%	(Yoshida et al., 2018)
Cr	% Cr input	25%	11%	50%	(Yoshida et al., 2018)
Cu	% Cu input	8.0%	1.8%	25%	(Yoshida et al., 2018)
F	% F input	100%	98%	100%	
Fe	% Fe input	32%	15%	50%	(Yoshida et al., 2018)
Hg	% Hg input	38%	3.3%	60%	(Yoshida et al., 2018)
K	% K input	96%	92%	100%	(Yoshida et al., 2018)
Mg	% Mg input	92%	90%	94%	(Yoshida et al., 2018)
Mn	% Mn input	51%	50%	51%	(Yoshida et al., 2018)
Mo	% Mo input	56%	50%	63%	
N	% N input	9.4%	8.1%	11%	(Yoshida et al., 2018)
Ni	% Ni input	57%	52%	63%	(Yoshida et al., 2018)
P	% P input	6.9%	6.6%	7.3%	(Yoshida et al., 2018)
Pb	% Pb input	6.4%	2.7%	10%	(Yoshida et al., 2018)
Sb	% Sb input	46%	43%	50%	(Yoshida et al., 2018)
Se	% Se input	72%	50%	89%	(Yoshida et al., 2018)
Sn	% Sn input	37%	32%	41%	(Yoshida et al., 2018)
Zn	% Zn input	18%	7.9%	30%	(Yoshida et al., 2018)
V	% V input	32%	14%	50%	(Yoshida et al., 2018)

3.11.1 Cost

The only costs that were included were the cost of the chemicals (unitary costs in Table 38) and the energy consumption (unit costs in section 3.17.2).

*Table 38: Energy and chemicals consumption of the wastewater treatment plant treating the reject water from the dewatering unit. *Min and max calculated based on the uncertainty of the electricity. **Min and max calculated based on the uncertainty of $FeCl_3$. All the parameters were modeled with a triangular uncertainty distribution of ±20%.*

Source	Unit	Mode	Reference
Iron (III) chloride ($FeCl_3$)	EUR2019/t	421	ecoinvent 3.6
Iron sulfate ($FeSO_4$)**	EUR2019/t	91	ecoinvent 3.6
Aluminum sulfate ($Al_2(SO_4)_3$)**	EUR2019/t	230	ecoinvent 3.6

3.12 Incineration with energy recovery

3.12.1 Energy internal consumption

Table 39 shows the internal energy consumption of all the incineration plants modeled in this study.

Table 39: Electricity and heat consumption for the incineration of food waste, sewage sludge, and biorefinery residues. All the data were modeled with a triangular uncertainty distribution.

Process	Mode	Min	Max	References
Electricity consumption [kWh / t wet weight input]	122	91	152	(Ecocenter, 2019; Jungbluth et al., 2007; Yoshida et al., 2018)
Heat consumption [MJ / t wet weight input]	469	99	839	(Jungbluth et al., 2007)

3.12.2 Gross energy efficiency

The energy efficiencies of the incineration plants define how much of the entering energy is converted into electricity and heat. The generated energy can either be used internally or sold to the grid. The possibility to sell heat to the grid assumes the presence of a district heating grid that is very developed in Northern Europe but quite rare in Southern Europe. Table 40 shows the gross energy, electricity and heat efficiency of the incineration plants in all the clusters.

Due to the need of modeling independent variables in the Monte Carlo analysis, we modeled the electrical efficiency as the difference between the total energy efficiency and the hear efficiency.

*Table 40: Total gross energy, gross electricity and gross heat efficiency of the incinerators treating only food waste in the five clusters. All the efficiencies were modeled with a triangular uncertainty distribution. *the total energy efficiency can be higher than 100% because it is calculated on the low heating value.*

Process	Gross energy efficiency	Gross heat efficiency	Gross electricity efficiency	References
Barcelona	33%	10%	22%	• Based on direct communication with the clusters. • Since the efficiencies represent exactly the plants in the cluster, a low uncertainty was assumed (±10)%.
Copenhagen	107%*	82%	25%	• Based on the two plants in the Copenhagen area (ARC and Vestforbrænding). • The uncertainty is based on the minimum and maximum efficiency found in these plants • Uncertainty gross energy efficiency: between 101% and 113% • Uncertainty gross heat efficiency: between 82% and 83%.
Lisbon	26%	4.5%	22%	• No information on the cluster was found. Our data were based on the generic incinerator found in Portugal where only electricity producing plants were found (Reimann, 2012). The efficiency is for average European plants producing only power. • Uncertainty gross energy efficiency: between 25% and 35% (Hulgaard and Vehlow, 2011)
South Wales	33%	13%	20%	• No information on the cluster was found. Our data were based on the generic incinerator found in the United Kingdom (Reimann, 2012). • Uncertainty gross energy efficiency: between 26% and 52% • Uncertainty gross heat efficiency: between 4.5% and 37%
Trento	43%	23%	20%	• Based on the input and output energy in the Bergamo incinerator (Ecocenter, 2019). • Since the efficiencies represent exactly the plants in the cluster, a low uncertainty was assumed (±10)%.

The incineration plants treating sewage sludge (with or without anaerobic digestion) generate energy that is usually simply used internally in the wastewater treatment plants to reduce operational costs. The same efficiencies were assumed for the incineration plants treating sewage sludge and biorefinery residues.

Table 41 shows the minimum and maximum efficiencies calculated as the minimum and maximum efficiencies of the incineration plants treating municipal solid waste (described in Table 40), excluding

Copenhagen since these high values were not found in the case of incinerators treating sewage sludge. Due to the uncertainty of these data, the uncertainty range was quite broad and the efficiencies were modeled with a uniform distribution where the mode was the average between the minimum and maximum.

Table 41: Gross energy and heat efficiency in all the clusters for the incineration plants treating sewage sludge and the biorefinery residues. The efficiencies were modeled with a uniform uncertainty distribution, where the mode was the average between the minimum and the maximum.

Process	Min	Max
Gross energy efficiency	26%	43%
Gross heat efficiency	4.5%	23%

3.12.3 Ancillary material and emissions

Table 42 shows the ancillary material consumption, the input specific emissions, and the process specific emissions of the incineration plants based on data about incineration plants treating municipal solid waste (Arena and Di Gregori, 2013; Beylot and Villeneuve, 2013; Møller et al., 2013; Turconi et al., 2011) and the Danish plants for sewage sludge Avedøvre and Lynetted (Biofos, 2015).

A part for the energy efficiency, no difference is assumed between the incineration of food waste, sewage sludge or biorefinery residues, because similar ranges were found in the different articles and reports. However, the incineration of sewage sludge and biorefinery residues also included the combustion of petrol as an auxiliary fuel (based on Yoshida et al. (2018).

*Table 42: Ancillary material consumption, input specific emissions (to air) and process specific emissions (to air) of the incineration plants treating municipal solid waste, sewage sludge (with or without anaerobic digestion), and biorefinery residues (with or without anaerobic digestion). *23% of the reported particular matter (PM) were assumed to be $PM_{2.5}$ and 77% between $PM_{2.5}$ and PM_{10}* (Fazio et al., 2018). *All the data were modeled with a triangular uncertainty distribution.*

		Unit	Mode	Min	Max
Ancillary materials	Water	kg	623	397	1,720
	Activated carbon	kg	0.8	0.6	1.0
	Ammonia	kg	1.5	1.5	1.5
	Sodium hydroxide	kg	1.1	0.0	2.6
	Hydrogen chloride gas	kg	5.6E-03	3.2E-03	9.7E-03
	Calcium carbonate CaCO3	kg	4.8	4.0	5.7
	Hydrated lime	kg	1.7	0.3	3.0
	Petrol (only for sewage sludge and biorefinery residues)	kg	0.74		
Input specific emissions	Carbon	% C input	9.9E-01	9.8E-01	1.0E+00
	Chlorine	% Cl input	3.8E-03	1.1E-03	6.5E-03
	Sulfur	% S input	1.0E-02	9.9E-04	2.0E-02
	Arsenic	% As input	1.2E-04	4.6E-05	2.0E-04
	Cadmium	% Cd input	6.4E-05	2.4E-05	1.0E-04
	Chromium	% Cr input	3.9E-04	1.5E-04	6.4E-04
	Cupper	% Cu input	2.4E-05	2.1E-05	2.6E-05
	Aluminum	% Al input	2.6E-05	9.9E-06	4.2E-05
	Antimony	% Sb input	1.2E-03	4.5E-04	1.9E-03
	Iron	% Fe input	4.9E-06	1.9E-06	7.9E-06
	Calcium	% Ca input	1.3E-06	5.0E-07	2.1E-06
	Potassium	% K input	2.2E-04	8.4E-05	3.6E-04
	Magnesium	% Mg input	2.7E-05	1.0E-05	4.4E-05
	Lead	% Pb input	3.0E-04	8.1E-06	5.9E-04
	Zinc	% Zn input	1.3E-04	0.0E+00	2.5E-04
	Nickel	% Ni input	3.3E-04	1.3E-04	5.3E-04
	Mercury	% Hg input	7.5E-03	2.9E-03	1.2E-02
Process specific emissions	Carbon monoxide	kg/t wet weight input	1.93E-02	2.40E-03	2.31E-01
	Dioxins	kg/t wet weight input	1.08E-10	1.21E-11	1.02E-09
	Hydrogen Chloride (HCl)	kg/t wet weight input	9.00E-03	7.00E-04	4.73E-02
	Hydrogen fluoride (HF)	kg/t wet weight input	6.60E-04	5.00E-05	2.70E-03
	NO_x	kg/t wet weight input	5.57E-01	1.10E-01	2.29E+00
	SO_2	kg/t wet weight input	3.84E-03	7.00E-04	2.63E-01
	PM*	kg/t wet weight input	2.44E-03	3.16E-05	3.87E-02

	NH_3	kg/t wet weight input	4.80E-03	1.00E-03	3.48E-02

3.12.4 Costs

The costs included in the incineration were the annualized CAPEX (Table 43), the CAPEX maintenance and insurance (as described in section 3.2), the salary of the employees (number of employees in Table 43 and unitary costs in section 3.19), the ancillary material consumption (unitary costs in Table 43), and the energy consumption (unitary costs in section 3.17.2). A 20% reserve factor A 20% was assumed based on Cimpan et al. (2016a).

*Table 43: Data used in the life cycle costing modeled with a triangular uncertainty distribution. *assumed a 20% relative uncertainty. CAPEX: capital expenditures.*

Process	Unit	Mode	Min	Max	References
Annualized CAPEX	EUR2019/t waste incinerated	51	20	86	(Energinet, 2020; EPEM SA, 2011; Hestin et al., 2015; Iaboni and De Stefanis, 2007; Martinez-Sanchez et al., 2016, 2015; Moretto and Favot, 2017; RDC-Environment and Pira International, 2003; Tonini et al., 2020)
Number of employees	no/t waste incinerated	2.5E-04	5.0E-05	5.5E-04	(Hestin et al., 2015; Iaboni and De Stefanis, 2007; Martinez-Sanchez et al., 2016, 2015; RDC-Environment and Pira International, 2003)
Bottom ash disposal	EUR2019/kg bottom ash	100	50	129	(Iaboni and De Stefanis, 2007; Martinez-Sanchez et al., 2016)
Fly ash disposal	EUR2019/kg fly ash	310	255	366	(Iaboni and De Stefanis, 2007)
Petrol	EUR2019/kg	0.91*			ecoinvent 3.6
Carbon	EUR2019/kg	1.20*			ecoinvent 3.6
Ammonia	EUR2019/kg	0.45*			ecoinvent 3.6
Sodium hydroxide	EUR2019/kg	0.24*			ecoinvent 3.6
Hydrogen chloride (HCl)	EUR2019/kg	0.16*			ecoinvent 3.6
Calcium carbonate	EUR2019/kg	0.58*			ecoinvent 3.6
Lime	EUR2019/kg	0.14*			ecoinvent 3.6

3.13 Mechanical biological treatment: stabilization and pre-treatment

A part of the currently generated residual waste in the clusters of Barcelona, Lisbon, and Trento is treated in different types of mechanical biological plants.

Three types of mechanical biological plants were modeled:

- Anaerobic digestion of the fine fraction followed by dewatering, composting, and landfilling (cluster of Lisbon)
- Mechanical biological stabilization (MBS), where the majority of waste is incinerated after a biological process (Barcelona)
- Mechanical biological pre-treatment (MBP), where the majority of waste is landfilled after a biological process, and a small part is incinerated (Barcelona and Trento).

The anaerobic digestion and composting were modeled as the source-separated food waste with a different methane potential (see section 3.6 and 3.8.7). The landfilling and the incineration were modeled as described in section 3.13.1 and 3.11.1.

The ancillary material and the energy consumption, and the degradation rates in the biological processes mass balance of MBP and MBS were based on Oros (2009) and (Grundmann, 2009), respectively (Table 44 and Table 45). The air emissions were assumed to be the same as composting (see section 3.8.7), as also done in Erikssen and Damgaard (n.d.).

Table 44: Ancillary material and energy consumption in the mechanical biological pre-treatment (MBP) and in the mechanical biological stabilization (MBS) for food waste. The parameters were modeled with a triangular uncertainty distribution having an uncertainty of ±20%.

		Unit	Mode
MBS	Electricity	kWh/t	120
	Natural gas (combusted in an industrial boiler)	MJ/t	2.4
	Water	l/t	116
MBP	Electricity	kWh/t	40
	Natural gas (combusted in an industrial boiler)	MJ/t	3.7
	Sulfuric acid	kg/t	3.2
	Diesel (combusted in a wheel loader)	l/t	1.3

Table 45: Degradation rates of the biological processes of the mechanical biological pre-treatment (MBP) and in the mechanical biological stabilization (MBS) for food waste. The parameters were modeled with a triangular uncertainty distribution having an uncertainty of ±20%.

		Unit	Mode
MBS	% of food waste to the biological treatment	% food waste input	75%
	VS degradation in the biological treatment	% VS input	85%
	C degradation in the biological treatment	% C input	85%
	N degradation in the biological treatment	% N input	65%
	Water content of the compost prior to landfilling	% water	35%
MBP	Water evaporated	% water input	98%
	VS degradation	% VS input	72%
	C degradation	% C input	72%
	N degradation	% N input	55%

3.13.1 Costs

The only costs considered were the CAPEX based on the epem database (EPEM SA, 2011) and are described in Table 46

Table 46: Annualized capital expenditures (CAPEX) for the mechanical biological treatment plant modeled with a triangular uncertainty distribution.

	Unit	Mode	Min	Max	References
Annualized CAPEX	EUR2019/t	19	15	24	(EPEM SA, 2011)

3.14 Landfilling

The landfills were modeled as in the software EASETECH (Olesen and Damgaard, 2014). Due to the difficulties to find information on the specific landfills, we modeled the collection (for the first 55 years) and flaring rate (Table 47) with the range found in several European countries (Andreasi Bassi et al., 2017). The collection rate is assumed to be zero after 55 years.

Table 47: Collection (for the first 55 years) and flaring rate of the landfills. The collection rate is assumed to be zero after 55 years.

	Unit	Mode	Min	Max	References
Gas collection rate	% gas generated	50	30	70	Range found in Andreasi Bassi et al. (2017)
Gas flaring rate	% gas collected	45	20	70	Range found in Andreasi Bassi et al. (2017)

3.14.1 Cost

The budget cost of waste landfilling was assumed to equal to the gate fee. Since the gate fee does not include the landfilling tax (that is very different among countries) the same budget cost was assumed in the five clusters (Table 48).

Table 48: Landfilling gate fee modeled with a triangular uncertainty distribution.

	Unit	Mode	Min	Max	References
Gate fee	EUR2019/t	70	5	204	(cewep, 2020; EEA, 2013; Eunomia, 2002b)

3.15 Use-on-land: compost, digestate, and raw sewage sludge

3.15.1 Direct impacts

Compost, digestate, and raw sewage sludge are considered organic fertilizers when used on agricultural land. Generally, we differentiated among three substrates: 1) composted food waste or composted sewage sludge; 2) raw digestate from the anaerobic digestion of only food waste; 3) raw sewage sludge or raw digestate from the anaerobic digestion of sewage sludge. This section describes the direct environmental impacts due to the spreading of the aforementioned organic fertilizers, while section 3.16 describes how we modeled the mineral fertilizers that are avoided thanks to such spreading.

We included the following environmental impacts directly caused by the application of different substrates on the agricultural soil:

- The emissions caused by the presence of nitrogen in the organic material (NH_3, N_2O and NO_x to air, NO_3 and NO_4 to water). These emissions greatly depend on the soil. Our main references were Yoshida et al. (2016) and Yoshida et al. (2018) where the fate of N was modeled with the software DAISY for three countries (Denmark, Germany and Netherlands) and three types of soil (coarse sandy, sandy loam, and clayey). The variation of the country and of the soil was included in the uncertainty distribution (Table 51). Furthermore, the emissions of nitrogen oxides due to the denitrification in soil (kg NO_x) were modeled as 21% of the emitted kg of N_2O (Nemecek and Kägi, 2007).
- The emissions caused by the presence of phosphorus in the organic material (phosphate to water). The emissions of phosphate depend on the level of P saturation of the soil. We assumed that 5.5% of the input P was modeled as leached to water (50% to surface water and 50% to groundwater), with a minimum of 0.9% and a maximum of 9.6% (Jungbluth et al., 2007; Tonini et al., 2020, 2019; Yoshida et al., 2018).
- The emissions caused by the presence of carbon in the organic material (CO_2 and CH_4 to air). The remaining C is stored in soil. We assumed that between 0.01% (Ambus et al., 2001) and 0.2% (Czubaszek and Wysocka-Czubaszek, 2018) was emitted as CH_4 and between 2% and 10% of the input carbon was bound to soil (Boldrin et al., 2009).
- The emissions caused by the presence of heavy metals in the organic material (cadmium, chromium, mercury, nickel, lead and zinc to soil). 100% of the heavy metals contained in the input substrates were modeled as emitted to agricultural soil
- The diesel consumption of the trucks spreading the substrate. The diesel consumption was modeled differently in the case of compost or raw digestate/sewage sludge. In the first case, with a mode of 0.30 kg diesel per ton compost (Bernstad and la Cour Jansen, 2011), assuming the same relative uncertainty as for the digestate. In the second case, it was modeled with a mode of 0.22 kg diesel per ton wet weight, with a min of 0.83 and a maximum of 0.53 (Bernstad and la Cour Jansen, 2011; Khoshnevisan et al., 2018 and diesel consumption in the ecoinvent 3.6 (consequential) processes "liquid manure spreading, by vacuum tanker" in Canada and Switzerland).

Table 49: Percentage of input N emitted to air as NH_3 and N_2O and to water as NO_3. The nitrate to groundwater was modeled as a difference between nitrate total and nitrate to surface water. All parameters were modeled with a triangular uncertainty distribution.

	Compost from both food waste and sewage sludge			Raw digestate from food waste			Raw sewage sludge and digestate from sewage sludge		
	Mode	Min	Max	Mode	Min	Max	Mode	Min	Max
NH_3_N to air	1.6%	1.4%	1.9%	1.6%	1.4%	1.9%	1.9%	1.7%	2.2%
N_2O_N to air	3.6%	1.8%	5%	2.4%	1.8%	3.0%	3.0%	2.0%	4.0%
NO_3_N total	34%	28%	62%	59%	48%	70%	45%	39%	71%
NO_3_N to surface water	15%	0.9%	20%	11%	0.5%	14%	4%	2%	17%
NH_4_N to surface water	1.6%	1.6%	1.6%	7.5%	7.4%	7.6%	1.9%	0.2%	7.8%

3.15.2 Costs of spreading

Two different costs were assumed for the spreading of fertilizers on agricultural land depending on the substrate (compost or raw digestate/sewage sludge), as reported in Table 50.

Table 50: Costs (assumed as budget costs) of spreading digestate, compost, and mineral fertilizers on agricultural land

Process	Unit	Mode	Min	Max	References
Spreading digestate/raw sewage sludge	EUR2019/t digestate	4.8	3.9	5.8	(WRAP, 2016)
Spreading compost	EUR2019/t compost	3.9	2.6	5.1	(WRAP, 2016)

3.16 Avoided fertilizers

The use of organic fertilizers (e.g. compost) on agricultural land allows the nutrients (N, P, and K) to return to land, be absorbed by plants, and avoid the use of mineral fertilizers (production and use-on-land).

This section described how we modeled the avoided mineral fertilizers: their composition, meaning which mineral fertilizers are avoided (3.16.1); how much of these fertilizers is actually avoided (3.16.2), the avoided use-on-land of mineral fertilizers (3.16.2) and the avoided costs (3.16.4).

3.16.1 Composition

The avoided fertilizers were modeled as the non-constrained growing fertilizers in the same way as marginal technologies are modeled in consequential LCAs (Ekvall and Weidema, 2004).

The marginal fertilizers were calculated based on the projected capacity of N and P fertilizers between 2014 and 2023 (Figure 32) published by the International fertilizer association (IFA, 2020), since it was not possible to find projected capacity up to 2030. Table 51 shows the calculated marginal N and P fertilizers used in the model. No data were found for K fertilizers and potassium chloride was assumed to be the marginal K fertilizers as in other similar LCA studies (Tonini et al., 2019).

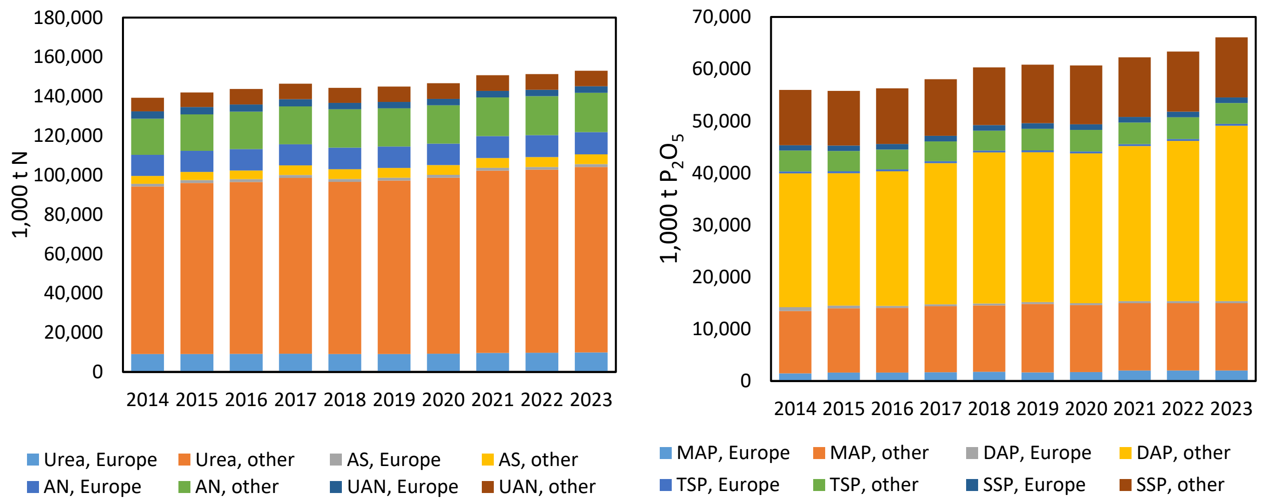

Figure 32: Global production capacity of N fertilizers (left) and P fertilizer (right) from 2014 to 2023 (IFA, 2020). AS: ammonium sulfate; AN: ammonium nitrate; UAN: urea ammonium nitrate; MAP: monoammonium phosphate; DAP: diammonium phosphate; TSP: triple superphosphate; SSP: single superphosphates

Table 51: Composition of the marginal N and P fertilizers.

	Marginal N fertilizer	Marginal P fertilizer
Urea, Europe	5.8%	
Urea, other	65%	
Ammonium sulfate (AS), Europe	0.12%	
Ammonium sulfate (AS), other	7.1%	
Ammonium nitrate (AS), Europe	3.9%	
Ammonium nitrate (AS), other	11%	
Urea ammonium nitrate (UAN), Europe		
Urea ammonium nitrate (UAN), other	7.3%	
Monoammonium Phosphate (MAP), Europe		5.3%
Monoammonium Phosphate (MAP), other		9.1%
Diammonium Phosphate (DAP), Europe		
Diammonium Phosphate (DAP), other		76%
Triple Superphosphate (TSP), Europe		
Triple Superphosphate (TSP), other		
Single Superphosphates (SSP), Europe		0.5%
Single Superphosphates (SSP), other		8.7%

3.16.2 Substitution factors

The substitution factors describe how much of the organic fertilizers avoids the production and the spreading of the marginal mineral fertilizers. There are several methods to quantify the substitution factors as summarized in Brockmann et al. (2018).

In this model, the N substitution factor was calculated as the ratio between the N harvested by the plants in the case of organic fertilizers (e.g. compost and digestate) and the N harvested by the plants in case of mineral fertilizer for the same type of soil based on the data found in Yoshida et al. (2016) and Bruun et al. (2016).

The P and K substitution factors were calculated based on the method presented in Tonini et al. (2019).

Table 52: Mineral fertilizers substitution factors for all the considered substrates modeled with a triangular uncertainty distribution.

	Mode	Min	Max
N substitution factor for compost from both food waste and sewage sludge	38%	30%	46%
N substitution factor for raw digestate from food waste	29%	26%	43%
N substitution factor for raw sewage sludge and digestate from sewage sludge	46%	37%	54%
P substitution factor for all the substrates	85%	42%	85%
K substitution factor for all the substrates	73%	66%	73%

3.16.3 Use-on-land

The avoided direct impacts of using on land mineral fertilizers were modeled similarly as for the organic fertilizers (section 3.15):

- N in N fertilizers was assumed to be emitted to air as NH_3 (Table 53), N_2O (Table 55) and NO_x (Table 55); and to surface and groundwater as nitrate (Table 55). The emissions of nitrogen oxides (kg NO_x) due to the denitrification in soil were modeled as 21% of the emitted kg of N_2O (Nemecek and Kägi, 2007) as in section 3.15.
- Each kg of N contained in urea was modeled as emitting 1.59 kg (min: 0.8, max: 1.59) kg fossil CO_2 to air (IPCC, 2006; Nemecek and Kägi, 2007).
- 5.5% of the P in P fertilizers was modeled as leached to water (50% to surface water and 50% to groundwater), with a minimum of 0.9% and a maximum of 9.6% (Jungbluth et al., 2007; Tonini et al., 2020, 2019; Yoshida et al., 2018) as in section 3.15.
- The emissions of heavy metals to agricultural soil were based on the heavy metal content of mineral fertilizers (Table 55, Table 56, and Table 57)
- Spreading mineral fertilizers requires 15 kg of diesel per ton N, P_2O_5 and K_2O, with a minimum of 4.1 and a maximum of 31 (Bernstad and la Cour Jansen, 2011 and ecoinvent 3.6 (consequential) consumption for the processes "fertilizing by broadcaster in Canada, Switzerland, and Brasil assuming an application of 170 kg N per hectare).

The sub-compartment for the emissions to air was “non-urban air or from high stacks”.

Table 53: Percentage of N from N mineral fertilizers emitted to air as ammonia modeled with a triangular uncertainty distribution. The mode for urea and ammonium sulfate was based on Asman (1992) as also implemented in ecoinvent 3.6 (consequential), while minimum and maximum were calculated ±40% since ammonia emissions have an uncertainty of 30/40% (Asman, 1992). Urea ammonium nitrate was calculated as an average between urea and ammonium sulfate as also done in ecoinvent 3.6 (Nemecek and Kägi, 2007). Ammonium nitrate was modeled as urea ammonium nitrate.

	NH_3_N to air per N input		
	Mode	Min	Max
Urea	15%	9%	21%
Ammonium sulphate	8%	5%	11%
Ammonium nitrate	2%	1%	3%
Urea ammonium nitrate	9%	5%	12%

Table 54: Percentage of N from N mineral fertilizers emitted to air as N_2O and to water as NO_3. All data were modeled with a triangular uncertainty distribution. The same emissions factors are assumed for all the N mineral fertilizers. The nitrate to groundwater was modeled as a difference between nitrate total and nitrate to surface water.

	Mode	Min	Max	Reference
N_2O_N	2.1%	3.1%	1.2%	(IPCC, 2019; Jungbluth et al., 2007; Yoshida et al., 2018)
NO_3_N total	27%	13%	39%	(Jungbluth et al., 2007; Yoshida et al., 2018)
NO_3_N to surface water	11%	0.5%	14%	Original data for ammonium nitrate (Yoshida et al., 2018)
NH_4_N to surface water	0.01%	0%	0.07%	Original data for ammonium nitrate (Yoshida et al., 2018)

Table 55: Heavy metal content of urea, ammonium sulfate, ammonium nitrate and urea ammonium nitrate expressed as kg heavy meatal per kg N. The data were modeled with a triangular uncertainty distribution, where the minimum and maximum were based on the heavy metals content used in ecoinvent 3.6 (Freiermuth, 2006) and in Agrybalyse (Koch and Salou, 2015).

	Urea			Ammonium sulphate			Ammonium nitrate and urea ammonium nitrate		
	[kg heavy metal/kg N]			[kg heavy metal/kg N]			[kg heavy metal/kg N]		
	Mode	Min	Max	Mode	Min	Max	Mode	Min	Max
Cd	2.7E-07	1.1E-07	4.3E-07	6.0E-07	2.4E-07	9.5E-07	1.4E-06	1.8E-07	2.5E-06
Cu	6.8E-06	6.5E-07	1.3E-05	2.0E-05	1.9E-05	2.0E-05	2.3E-05	2.1E-05	2.5E-05
Zn	5.0E-05	3.7E-06	9.6E-05	8.9E-05	3.4E-05	1.4E-04	9.4E-05	6.2E-06	1.8E-04
Pb	1.4E-06	4.3E-07	2.4E-06	5.0E-06	4.8E-06	5.2E-06	4.5E-06	2.2E-06	6.9E-06
Ni	2.3E-06	2.2E-07	4.4E-06	1.5E-05	8.6E-06	2.1E-05	2.5E-05	3.6E-06	4.7E-05
Cr	2.2E-06	0.0E+00	4.4E-06	2.2E-05	9.5E-06	3.4E-05	1.9E-05	1.5E-05	2.4E-05
Hg	4.3E-07	1.8E-07	8.7E-07	1.0E-23	9.6E-24	4.3E-07	3.6E-07	3.3E-07	7.0E-07

Table 56: Heavy metal content of monoammonium phosphate, diammonium phosphate, triple superphosphate, single superphosphate expressed as kg heavy meatal per kg P_2O_5. The data were modeled with a triangular uncertainty distribution, where the minimum and maximum were based on the heavy metals content used in ecoinvent 3.6 (Freiermuth, 2006) and in Agrybalyse (Koch and Salou, 2015).

	Monoammonium phosphate			Diammonium phosphate			Triple superphosphate			Single superphosphate		
	[kg heavy metal/ kg P_2O_5]			[kg heavy metal/ kg P_2O_5]			[kg heavy metal/ kg P_2O_5]			[kg heavy metal/ kg P_2O_5]		
	Mode	Min	Max	Mode	Min	Max	Mode	Min	Max	Mode	Min	Max
Cd	7.0E-05	2.6E-05	1.1E-04	7.2E-05	3.1E-05	1.1E-04	7.8E-05	4.3E-05	1.1E-04	5.9E-05	5.3E-05	6.5E-05
Cu	7.4E-05	4.9E-05	9.8E-05	7.8E-05	5.8E-05	9.8E-05	8.3E-05	6.7E-05	9.8E-05	1.1E-04	9.7E-05	1.2E-04
Zn	5.4E-04	4.2E-04	6.5E-04	5.8E-04	5.0E-04	6.5E-04	7.7E-04	6.5E-04	8.8E-04	9.3E-04	8.5E-04	1.0E-03
Pb	5.3E-06	3.0E-06	7.6E-06	5.6E-06	3.5E-06	7.6E-06	7.7E-06	7.6E-06	7.8E-06	3.0E-04	1.2E-05	5.8E-04
Ni	7.3E-05	5.1E-05	9.6E-05	7.8E-05	6.0E-05	9.6E-05	8.3E-05	7.0E-05	9.6E-05	1.2E-04	1.1E-04	1.3E-04
Cr	4.7E-04	3.7E-04	5.7E-04	5.0E-04	4.3E-04	5.7E-04	5.0E-04	4.3E-04	5.7E-04	4.3E-04	3.4E-04	5.1E-04
Hg	1.0E-23	7.9E-24	5.8E-07	1.0E-23	8.7E-24	5.8E-07	2.6E-07	2.6E-07	3.8E-07	5.8E-07	5.3E-07	1.1E-06

Table 57: Heavy metal content of potassium chloride expressed as kg heavy meatal per kg K_2O. The data were modeled with a triangular uncertainty distribution, where the minimum and maximum were based on the heavy metals content used in ecoinvent 3.6 (Freiermuth, 2006) *and in Agrybalyse* (Koch and Salou, 2015).

	Potassium chloride [kg heavy metal/kg K_2O]		
	Mode	Min	Max
Cd	2.8E-07	1.0E-07	4.6E-07
Cu	7.7E-06	7.1E-06	8.3E-06
Zn	4.4E-05	1.0E-05	7.7E-05
Pb	5.4E-06	1.6E-06	9.2E-06
Ni	4.4E-06	3.5E-06	5.3E-06
Cr	2.9E-06	2.6E-06	3.3E-06
Hg	1.0E-07	9.2E-08	1.8E-07

3.16.4 Costs

The budget cost of mineral fertilizers was based on the market price of urea, potassium chloride, diammonium phosphate (DAP), and triple superphosphate (TSP) reported by the World Bank (World Bank, 2020). The market costs of urea were assumed representative for all the N fertilizers, potassium chloride for all the K fertilizers, and the average between diammonium phosphate and triple superphosphate for the P fertilizers (Table 58). The budget cost was calculated by subtracting the profit share (Table 58) from the market prices.

Table 58: Market costs of urea, potassium chloride and average between diammonium phosphate (DAP) and triple superphosphate (TSP) reported by the World Bank (World Bank, 2020) modeled with a triangular uncertainty distribution. We assumed that the cost of urea was representative for all N fertilizers, potassium chloride for all K fertilizers, and the average between DAP and TSP for all P fertilizers. The market costs were corrected to calculate the budget costs by subtracting the profit share (eurostat, 2019) from the market prices.

	Mode	Min	Max
N fertilizers [EUR2019/t N]	462	386	532
P fertilizers [EUR2019/t P_2O_5]	565	561	760
K fertilizers [EUR2019/t K_2O]	369	304	434
Average profit share for mineral fertilizers in the European Union [% market price]	8%	3%	18%

Table 59 shows the cost of spreading mineral fertilizers assuming different application rates.

Table 59: Costs (assumed as budget costs) of spreading mineral fertilizers on agricultural land assuming different application rates.

Process	Unit	Mode	Min	Max	References
Spreading N mineral fertilizers	EUR2019/t N	213	63	266	(Loncaric et al., 2013)
Spreading P mineral fertilizers	EUR2019/t P_2O_5	418	304	532	(Loncaric et al., 2013)
Spreading K mineral fertilizers	EUR2019/t K_2O	139	101	176	(Loncaric et al., 2013)

3.17 Consumed and avoided energy (electricity, space heating, diesel)

3.17.1 Marginal electricity and space heating

The marginal electricity and space heating in each cluster was calculated as the non-constrained growing technologies between 2030 and 2015 as traditionally done in consequential LCAs (Ekvall and Weidema, 2004).

The marginal electricity was based on the information published for the reference scenario in the GECO report 2018 (Keramidas et al., 2018). Table 60 illustrates the composition of the marginal electricity and the average (in 2020) used in the framework scenario e).

Table 60: Marginal (growing technologies between 2030 and 2015) and average (in 2020) electricity used in this study

	Spain		Denmark		Portugal		UK		Italy	
	Marginal	Average	Marginal	Average	Marginal	Average	Marginal	Average	Marginal	Average
Bio		3.0%		6.0%		4.4%		5.4%		8.2%
Solid Coal	7.8%	2.0%		35%		25%		33%		10%
Solid Lignite		2.6%								
Geothermal					3.2%					2.0%
Hydro Lakes	12%	12%			18%	11%		1.2%	12%	12%
Hydro River		1.7%			10%	16%			10%	9%
Natural gas conventional			3.1%	4.8%	3.0%		5.7%		1.9%	6.6%
Natural gas combined		16%	13%	3.4%		3.7%		18%		30%
Nuclear	7%	22%					28%	21%		
Oil		7.1%	3.3%			7.9%	1.4%	1.7%		2.9%
Solar Panels	50%	9.0%	19%	3.4%	13%	3.7%	26%	5.7%	42%	11%
Solar Plants		1.6%								
Wind Onshore	23%	23%	61%	39%	53%	28%	39%	12%	35%	8.0%
Wind Offshore				8.8%				2.1%		
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

The space heating (or residential heating) avoided due to the incineration plants was modeled on the data described in the report "Mapping and analyses of the current and future (2020 - 2030) heating/cooling fuel deployment (fossil/renewables)" prepared for the European Commission's forecasts (Fleiter et al., 2017). Table 61 illustrates the marginal space heat and the average (in 2020) used in the framework scenario f).

Table 61: Marginal (growing technologies between 2030 and 2015) and average (in 2020) space heat used in this study

	Spain		Denmark		Portugal		UK		Italy	
	Marginal	Average	Marginal	Average	Marginal	Average	Marginal	Average	Marginal	Average
Heat pumps				2.8%	13%		7.9%			6.8%
Biomass	77%	29%	72%	23%		39%	20%		13%	21%
Solar energy	23%	2.8%	28%		87%	5.6%	67%		87%	
District heating				44%			4.6%			2.2%
Electricity		11%		5.5%		11%		8.1%		12%
Fuel oil		25%		8.5%		29%		8.1%		7.4%
Natural gas		32%		16%		15%		84%		51%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

3.17.2 Costs

Table 62 shows the budget costs of electricity, space heating, and diesel used in this study.

The budget cost of electricity in each cluster is based on the average between the cost of electricity excluding taxes and levies for non-households (with a yearly consumption between 500 and 2,000 MWh) and households reported in Eurostat (Eurostat, 2019a) for the years 2018 and 2019.

The budget cost of space heat in each cluster is based on the average between the cost of natural gas excluding taxes and levies for non-households (with a yearly consumption between 10,000 and 100,000 GJ) and households reported in Eurostat (Eurostat, 2019b) for the years 2018 and 2019.

The budget cost of diesel in each cluster is based on the cost of automotive gas oil without taxes reported by the European Commission's oil bulletin for the year 2018 (Eurostat, 2018b).

Table 62: Budget cost (costs without taxes and VAT) of electricity, space heat, and diesel in each cluster based on Eurostat data (Eurostat, 2019a, 2019b, 2018b). **Based on the cost of natural gas.*

		Spain	Denmark	Portugal	UK	Italy
Electricity [EUR2019/kWh]	Mode	0.13	0.08	0.09	0.12	0.12
	Min	0.11	0.08	0.09	0.12	0.11
	Max	0.15	0.09	0.10	0.13	0.12
Space heat* [EUR2019/MJ]	Mode	0.013	0.009	0.012	0.010	0.011
	Min	0.011	0.007	0.012	0.009	0.010
	Max	0.015	0.010	0.013	0.010	0.013
Diesel [EUR2019/l]	Mode	0.62	0.66	0.61	0.55	0.59
	Min	0.57	0.59	0.55	0.50	0.55
	Max	0.66	0.72	0.65	0.60	0.64

3.18 Transport

All the transports were modeled with the ecoinvent 3.6 (consequential) process "transport, freight, lorry 16-32 metric ton, EURO6, RER". Table 63 shows the distances in km between the different steps of the food waste and sewage sludge treatment.

The distance between waste collection and the biorefinery was assumed to be the same as the distance between waste collection and anaerobic digestion plants.

Table 63: Distances in km between the different steps of the food waste and sewage sludge treatment. All the distances were modeled with a triangular uncertainty distribution, excluding the cases in which there was only one plant. AD: anaerobic digestion; MBT: mechanical biological treatment plants

		Mode [km]	Min [km]	Max [km]	Reference
Barcelona	From collection to AD plant	16	10	22	Based on the geographical position of the AD plants
	From collection to MBT plants	36	10	60	Based on the geographical position of the MBT plants
	From collection to incineration and from mechanical biological drying to incineration	10	8	12	Based on the geographical position of the incineration plant. A ∓20% uncertainty was assumed.
	From mechanical biological stabilization to landfill	60	48	72	Based on the geographical position of the landfill. A ∓20% uncertainty was assumed.
	From dewatering to agricultural land	40	32	48	Based on internal communication with the cluster. A ∓20% uncertainty was assumed.
Copenhagen	From collection to AD plant (to the pulping + to the AD plant)	127	102	152	Based on internal communication with the cluster. A ∓20% uncertainty was assumed.
	From the AD plant to agricultural land	10	8	12	Based on internal communication with the cluster. A ∓20% uncertainty was assumed.
	From collection to incineration	14	7	20	Based on the geographical position of the incineration plants.
Lisbon	From collection to AD plant	15	12	18	Based on the geographical position of the AD plant. A ∓20% uncertainty was assumed.
	From collection to MBT	30	24	36	Based on the geographical position of the incineration plant. A ∓20% uncertainty was assumed.
	From collection to landfill	30	24	36	Based on the geographical position of the landfills. A ∓20% uncertainty was assumed.
	From collection to incineration plant	30	24	36	Based on the geographical position of the incineration plant. A ∓20% uncertainty was assumed.
	To agricultural land	123	88	163	Assumed the same distance as the composting plants for sewage sludge.
South Wales	From collection to composting plants	60	30	90	Based on the geographical position of the composting plants.
	From collection to incineration	32	4	60	Based on internal communication with the cluster.

	To agricultural land (food waste)	12.5	10	15	The maximum is based on internal communication with the cluster. The mode and the minimum were assumed.
	To agricultural land (sewage sludge)	24	16	64	Based on internal communication with the cluster.
Trento	From collection to AD	18	5	30	Assumed the same distance as the composting plants
	From collection to composting	18	5	30	The minimum was assumed if the plant was in Trento, the maximum was the distance to Rovereto's plant. The mode was the average between minimum and maximum.
	From collection to incineration	31	10	56	The minimum was assumed if the plant was in Trento, the maximum was the distance to Bolzano's incinerator. The mode was the average between minimum and maximum.
	From collection to mechanical biological drying	26	21	31	The mode was based on the geographical position of the MBT plant. A ∓20% uncertainty was assumed.
	From collection to landfill	27	5	47	Based on the geographical position of the landfills
	To agricultural land	55	10	100	Assumed. The larger uncertainty range is to model this uncertainty.

The cost of transport (assumed to be equal to the budget cost) was based on data from different countries and was assumed to be equal in the 5 clusters (Table 64).

Table 64: Cost (assumed to be budget cost) of transport modeled with a triangular uncertainty distribution.

	Mode	Min	Max	Reference
Cost of transport [EUR2019/t/km]	0.077	0.005	0.108	(Eco-emballages, 2014; Gibbs et al., 2014; Hestin et al., 2015; Villanueva and Eder, 2014)

3.19 Salary

The budget costs of the salary were defined as the net earnings of the workers. The net earning of "professionals" was calculated by combining the average net earnings in 2018 for a "single person without children, 100% of an average worker" (Eurostat, 2019c) and the information found in the "structure of earnings survey 2014" (Eurostat, 2018c). Table 65 shows the net earnings in each cluster.

Table 65: Calculated net earning of a professional in the five clusters. The mode was calculated as the average between the data in 2018 and in 2019. The salaries were modeled with a triangular uncertainty distribution.

	Unit	Mode	Min	Max
Barcelona	EUR2019/year	29,326	29,020	29,633
Copenhagen	EUR2019/year	43,386	43,098	43,675
Lisbon	EUR2019/year	22,314	22,137	22,491
South Wales	EUR2019/year	45,816	44,870	46,762
Trento	EUR2019/year	27,846	27,666	28,027

3.20 PHA from first-generation biomass

Three PHAs from first-generation biomass were compared to the PHA from urban biowaste, two of which were derived from sucrose in sugarcane (Harding et al., 2007; Kookos et al., 2019) and one from glucose in maize (Gerngross, 1999). Table 66 shows the life cycle inventory of these three PHAs. Finally, the waste management depended on the cluster and on the type of waste management (e.g. incineration or landfilling).

*Table 66: Life cycle inventory of the three PHAs from first-generation biomass modeled in this study. All the values are reported per kg PHA produced. *modeled with the process "wastewater, average, market for wastewater, average, Europe without Switzerland"; **modeled with the process "chemical factory, organics, RER"*

		(Harding et al., 2007)	(Gerngross, 1999)	(Kookos et al., 2019)
Sucrose (from cane sugar)	kg	1.81		5.9
Glucose	kg		3.33	
Soybean oil	kg			
Electricity	kWh	1.10	5.32	1.274
Steam	kg	4.893	2.683	0.951

Natural gas	MJ	2.123		
Process water	kg	65.2	26	
Acids e other:				
H_2SO_4	kg	0.00302		
H_3PO_4 (conc.)	kg	0.00812		
H_2O_2	kg	0.05290		
Optimase L660 (MKC)	kg	0.00240		
NH3	kg			0.166
CO2 fossil to air	kg			6.5
NaOCl	kg			0.219
Sulphates:				
MgSO4.7H2O	kg	0.0209		
K2SO4	kg	0.0186		
(NH4)2SO4	kg	0.0148		
Na2SO4	kg	0.0030		
ZnSO4.7H2O	kg	0.0012		
MnSO4.H2O	kg	0.0009		
FeSO4.7H2O	kg	0.0008		
CuSO4.5H2O	kg	0.0001		
CaCl2.2H2O	kg	0.0023		
NaHPO4	kg	0.0001		
Waste				
Dilute wastewater*	m3	0.0652		
capital good**	unit	4E-10		

The budget costs were calculated by subtracting the profit share to the market price of fossil polymers (Table 67).

Table 67: Market prices of PHA first-generation biomass and profit share of primary forms of plastic in the European Union modeled with a triangular uncertainty distribution.

	Unit	Mode	Min	Max	Reference
PHA from first-generation biomass	EUR2019/kg	3.4			(Fantinel, 2019)
Profit share*	% market price	8.4%	3.2%	18%	(eurostat, 2019)

3.21 Fossil plastic

PHA from urban biowaste was compared to three granules made of fossil plastic, polyurethane (PUR), low-density polyethylene (HDPE), and polypropylene (PP). Table 68 shows the processes from ecoinvent 3.6 (consequential) that were used to model the production of these granules.

Table 68: Processes used to model the production of polyurethane (PUR), low-density polyethylene (HDPE), and polypropylene (PP)

	Process ecoinvent 3.6 consequential
PUR	"polyurethane, flexible foam, RER"
LDPE	"polyethylene, low density, granulate, RER"
PP	"polypropylene, granulate, RER"

The budget costs were calculated by subtracting the profit share to the market price of fossil polymers (Table 69).

Table 69: Market prices of polyurethane (PUR), low-density polyethylene (HDPE), and polypropylene (PP) and profit share of primary forms of plastic in the European Union modeled with a triangular uncertainty distribution.

	Unit	Mode	Min	Max	Reference
PUR	EUR2019/kg	2.7	2.5	3.0	(Fantinel, 2019)
LDPE	EUR2019/kg	1.5	1.2	1.7	
PP	EUR2019/kg	1.4	1.2	1.6	
Profit share*	% market price	8.4%	3.2%	18%	(eurostat, 2019)

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