Supplementary material for

"Life cycle assessment of existing and alternative options for municipal solid waste management in Saint Petersburg and Leningrad region, Russia"

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Abbreviations

AD	Anaerobic Digestion
ADP_f	Abiotic Depletion Potential (fossil fuels)
AP	Acidification Potential
APC	Air Pollution Control
DOC	Degradable Organic Carbon
EP	Eutrophication Potential
GWP	Global Warming Potential
HDPE	High-density Polyethylene
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LFG	Landfill Gas
MCF	Methane Correction Factor
MSW	Municipal Solid Waste
NMVOC	Non-methane Volatile Organic Compounds
NSR	Normalized Sensitivity Ratio
PET	Polyethylene Terephthalate
RDF	Refuse Derived Fuel
SR	Sensitivity Ratio
SNCR	Selective Non-Catalytic Reduction

1 Reform of MSW management in Saint Petersburg and the Leningrad region

Reform of the waste management system in Saint Petersburg and the Leningrad region, as in the rest of Russia, was started in 2017-2019. In terms of waste handling practices, the reform aims to increase the amount of MSW sent to sorting and for utilization (meaning mainly material and energy recovery) and eliminate unauthorized dumps [85]. To facilitate increased rates of MSW sorting and utilization, additional capacity for waste sorting has been planned in each region.

Thus far, the federal city of Saint Petersburg and the Leningrad region have developed separate reform plans despite their closely linked MSW management systems. Existing MSW management systems and targeted developments are currently described in regional waste management plans drafted by the Waste Management Committee of the Leningrad Region [35] and the Committee for the Improvement of Saint Petersburg [41]. New facilities are planned in the Leningrad region to cover the needs of both areas. Those installations include waste sorting facilities in the towns of Gatchina and Kingisepp. At the same time, the plan for Saint Petersburg includes an expansion of the MPBO-2 plant, which would allow the waste treatment targets to be reached independently. It would appear that, according to current planning documents, there is some overlapping of plans for additional sorting capacity.

In this study, the development of the infrastructure planned in the Leningrad region is considered in preference to infrastructural changes planned in Saint Petersburg. Such a choice is determined by criticism of the MPBO-2 sorting plant expansion in Saint Peterburg [86], as well as lower availability of data on technologies being proposed for this plant.

2 Inventory data

2.1 Waste collection and transportation

Table S1. LCI data on waste collection and transportation in Saint Petersburg

District	MSW generation, share [41]	Distances, km[1]			
		Districts-> sorting/transfer stations		Sorting/transfer stations-> incineration plant	Sorting/transfer stations-> landfills
Vyborgsky	0.08	MPBO-2	30	65	25
Kalininsky	0.13		20		
Krasnogvardeisky	0.05		10		
Kronstadt	0.01		60		
Kurortny	0.02		70		
Nevsky	0.08		15		
Petrogradsky	0.03		25		
Primorsky	0.06		40		
Tsentralny	0.06		15		
Admiralteysky	0.04	Staroobryadcheskaya	5	45	40
Vastleostrovsky	0.05		15		
Kirovsky	0.08		15		
Frunzensky	0.07		15		
Kolpinsky	0.04	Sinergiya	5		50
Krasnoselsky	0.08	Predportovaya	10	40	120
Moskovsky	0.06		10		
Petrodvortsovy	0.03		35		
Pushkinsky	0.03	TEK	20	35	115

[1] Numbers are rounded up to nearest 5

Collection and transportation are modelled using unit processes from GaBi database: “GLO: Truck, Euro 5, 12 - 14t gross weight / 9,3t payload capacity” (in-city collection of MSW in Saint Petersburg) and “GLO: Truck-trailer, Euro 5, 28 - 34t gross weight / 22t payload capacity” (transportation of MSW from transfer stations and sorting facilities in Saint Petersburg and waste collection and transportation in the Leningrad region).

Table S2. LCI data on waste collection and transportation in the Leningrad region

District	MSW generation, share [35]	Distances, km[1]			
		Districts-> sorting/transfer stations		Sorting/transfer stations-> incineration plant	Sorting/transfer stations-> landfills
Podporozhsky	0.02	Kostsept EKO	60		90
Lodeynopolsky	0.02		15		
Kingisepp	0.04	Kingisepp plant	10	50	0
Sosnovoborsky	0.04		65		
Priozersky	0.03	Traktornoe plant	30		0
Slantsevsky	0.02	Slantsi plant	20	65	0
Volkhovsky	0.02	Kuti plant	35	75	0
Kirishsky	0.04	Lel' EKO	10		80
Vsevolozhsky	0.20	Lepsari plant	25		40
Volosovsky	0.02	Profspetstrans	20		65
Vyborgsky	0.12	SadServis	90		85
Boksitogorsky	0.02	-	-		15
Gatchinsky	0.14	Gatchina plant	5	30	5
Kirovsky	0.07	-	-		35
Lomonosovsky	0.04	-	-	40	60
Lugsky	0.04	-	-		40
Tikhvinsky	0.04	-	-		15
Tosnensky	0.06	-	-		25

[1] Numbers are rounded up to nearest 5

All trucks are diesel-driven; diesel supply is modeled using "RU: Diesel mix at filling station (100% fossil)" unit process.

Table S3. LCI data on transportation of recyclable materials

Sorting stations	Distances to recycling facilities, km[1]					
	Aluminum	Steel	Paper, cardboard	Glass	PET	HDPE
MPBO-2	20	500	180	520	45	680
Staroobryadcheskaya	25					
Sinergiya	20					
Predportovaya	10					
TEK	20					
Gatchina plant	45					
Kingisepp plant	130		240		135	
Traktornoe plant						
Kuti plant						
Lel' EKO						
Kontsept EKO	125		190		130	
Slantsi plant						
Lepsari plant						
Profspetstrans						
SadServis						

[1] Numbers are rounded up to nearest 5

2.2 Landfilling

Only methane emissions are considered in LFG emissions. Methane generation potential (kg_{CH4}/kg_{waste}) of waste decomposition is calculated based IPCC default model [42] using the equation:

$$L_0 = DOC \times DOC_f \times MCF \times F \times \frac{16}{12},$$

where DOC – degradable organic carbon, kg_C/kg_{waste},

DOC_f – share of degradable organic carbon degraded,

MCF – CH_4 correction factor, share,

F – a fraction of CH_4 in landfill gas, share,

$\frac{16}{12}$ – correlation between carbon and methane content.

Table S4. LCI data on landfilling

Parameter	Value	Unit	Reference
CH_4 oxidation factor	0.1	share	[42]
CH_4 correction factor	0.6	share	[42]
CH_4 fraction in LFG	0.5	share	[42]
Leachate generation	0.2	g/g_{MSW}	[45]
P in leachate	13.95	mg/dm^3	[44]
N in leachate	3.075	mg/dm^3	[44]
Leachate density	1000	kg/m^3	Assumed
Diesel use	0.46	dm^3/Mg_{MSW}	[44]
Emissions from diesel combustion (a bulldozer)			
CO	14	g/ dm^3_{diesel}	[57]
HC	3.4	g/ dm^3_{diesel}	[57]
NO_x	21	g/ dm^3_{diesel}	[57]
SO_2	0.008	g/ dm^3_{diesel}	[57]
CO_2-eq. (CO_2, CH_4, N_2O)	2674	g/ dm^3_{diesel}	[57]

Table S5. Initial data for calculation of the methane generation potential

Waste fraction	DOC, kg_C/kg_{waste}	DOC_f, share	L_0, kg_{CH4}/kg_{waste}
Paper	0.4	0.37	0.059
Wood	0.43	0.21	0.036
Food	0.15	0.64	0.038
Textile	0.24	0.50	0.048
Reference	[87]	[43]	Calculated

Table S6. Additional LCI data on landfilling with LFG collection

Parameter	Value	Unit	Reference
LFG collection rate	53	%	[48]
LFG to flaring	40	% LFG collected	[44]
Gas engine electric efficiency	36	%	[44]
Emissions from gas engine			
NO_x	11.6	g/Nm^3_{CH4}	[49]
CO	8.46	g/Nm^3_{CH4}	[49]
Emissions from flare device			
NO_x	0.631	g/Nm^3_{CH4}	[49]
CO	0.737	g/Nm^3_{CH4}	[49]
CH_4	1	% CH_4 input	[49]
Efficiency of flaring	99	%	[44]

2.3 Data on MSW sorting facilities

Table S7. Sorting facilities/processes modelled

Facility/process	Scenario	MSW sorted, Mg/a	Materials separated: Metals	Glass	Plastics	Paper & cardboard	Screening reject	RDF	Reference
Saint Petersburg									
MPBO-2	all	169 000	+	+	+	+	+		[53]
Staroobtyadcheskaya	all	100 000	+		+	+	+	+	[34,46]
Predportovaya	all	100 000	+		+	+	+	+	
TEK	all	56 302	+	+	+	+			[35,50]
Sinergiya	all	41 386	+	+	+	+			[41]
Leningrad region									
MSW sorting, screening incl.	all	18 496 [1]	+	+	+	+	+		[50,7]
MSW sorting, screening excl.	all	65575 [1]	+	+	+	+			
Gatchina plant	1-4	500 000 [2]	+		+	+	+	+	[35]
Kingisepp plant	1-4	300 000	+	+	+	+	+		

[1] Allocation of waste mass treated with and without screening of fine fraction is based on capacities of sorting plants which reported the presence of the screening process in the referenced source.

[2] MSW generated in Saint Petersburg is assumed to be sorted in Gatchina plant.

2.4 MSW sorting processes

Table S8. LCI data on mechanical sorting of mixed waste

Parameter	Value	Unit	Reference
Electricity consumption	70	kWh/Mg_{MSW}	[88]
Separation efficiencies			
ferrous metals	39.5	% of initial fraction mass	Calculated based on recovery rates from [46] and data on MSW composition
aluminum cans	25.0	% of initial fraction mass	
plastics	36.2	% of initial fraction mass	
paper and cardboard	26.0	% of initial fraction mass	
screening reject	34.4	% of input MSW	[46]
RDF	25.0	% of input MSW	[46]

Table S9. LCI data on a sorting line with manual separation of recyclable materials from mixed waste

Parameter	Value	Unit	Reference
Electricity consumption			
screen included	4[1]	kWh/Mg_{MSW}	Based on [64]
screen excluded	3[2]	kWh/Mg_{MSW}	Based on [64]
Recovery rates			
ferrous metals	39.5	% of initial fraction mass	See in Table S8
aluminum cans	5.6	% of initial fraction mass	Calculated based on recovery rates from [51] and an assumption that overall recovery rate equals 3%
plastics	2.5	% of initial fraction mass	
paper and cardboard	2.6	% of initial fraction mass	
glass	5.7	% of initial fraction mass	
screening reject	34.4	% of input MSW	[46]

[1] The value is obtained for assumed equipment (conveyor – 6 pcs, drum feeder – 1, trommel screen – 1, magnet – 1, one-way baler – 1, two-way baler – 1) using the methodology from [64]

[2] The value is obtained for assumed equipment (conveyor – 4 pcs, drum feeder – 1, magnet – 1, one-way baler – 1, two-way baler – 1) using the methodology from [64]

Table S10. LCI data on a sorting line for source-separated waste fractions

Parameter	Value	Unit	Reference
Electricity consumption	15[1]	kWh/Mg_{MSW}	Based on [64]
Separation efficiencies			
ferrous metals	100	% of initial fraction mass[2]	[64]
aluminum cans	100	% of initial fraction mass[2]	[64]
plastics	100	% of initial fraction mass[2]	[64]
paper and cardboard	100	% of initial fraction mass[2]	[64]
glass	98	% of initial fraction mass[2]	[64]

[1] The value is obtained according to the process flow given for source-separated materials sorting in [64] and using the methodology from [64]

[2] The initial fraction constitutes 70% of the flow leaving the other 30% as contaminants (mixed MSW)

2.5 Composting of organic fraction

Table S11. LCI data on windrow composting

Parameter	Value	Unit	Reference
Diesel need (windrow composting)	3	dm^3/Mg_{waste}	[56]
Electricity need (rotary drum)	62	kWh	[40]
Water need (rotary drum)	13	dm^3/Mg_{waste}	[40]
Diesel need (curing after the drum)	0.71	dm^3/Mg_{waste}	[55]
C content of organic matter	230 [1]	g/kg	[54]
N content of organic matter	7 [1]	g/kg	[54]
C degradation rate	66 [1]	%	[89]
N degradation rate	39 [1]	%	[54]
Compost output	60	%	[40]
Direct emissions from composting			
CH_4	1.5 [1]	$\%_{\text{degraded C}}$	[54]
N_2O	2 [1]	$\%_{\text{degraded N}}$	[54]
NH_3	83	$\%_{\text{degraded N}}$	[56]
NMVOC	2	$g/kg_{\text{wet waste}}$	[56]
Emissions from diesel combustion (wheel loader)			
CO	13	g/dm^3_{diesel}	[57]
HC	3.0	g/ dm^3_{diesel}	[57]
NO_x	17	g/ dm^3_{diesel}	[57]
SO_2	0.008	g/ dm^3_{diesel}	[57]
CO_2-eq. (CO_2, CH_4, N_2O)	2673	g/ dm^3_{diesel}	[57]
Mineral fertilizers substitution rates			
N fertilizer	2.85 [1]	$g/kg_{\text{waste treated}}$	[54]
P fertilizer	1.25 [1]	$g/kg_{\text{waste treated}}$	[54]
K fertilizer	3.90 [1]	$g/kg_{\text{waste treated}}$	[54]

[1] Averaged from the given interval

Share of organic matter in waste used in composting is calculated based on screening reject composition and organic content of source separated biowaste. Composition of screening reject is based on data from Staroobryadcheskaya sorting plant [46] (Table S12). Textile is assumed to contain 50% of biodegradable material. Screening reject < 50 mm is assumed to contain three times more food, wood, paper, and textile waste than related percentages given in Table S12. In this case, biodegradable matter constitutes over 45% of "screening reject < 50 mm" and 60% of total screening reject. Such a share of organic matter corresponds to data from Di Lonardo et al. [90].

Table S12. Composition of screening reject subject to composting [46]

Waste fraction	Mass, Mg/a	Share, %
Food waste	4 200	12.2
Paper	930	2.7
Cardboard	145	0.4
Wood	70	0.2
Textile	32	0.1
Plastics	165	0.5
Glass	4 350	12.6
Screening reject <50 mm	23 570	68.4
Other	981	2.9
Total	34 443	100.0

Produced compost is assumed to be fully utilized. In case of soil substitution, since it is the thickness of the isolation layer that is regulated in landfill operation, the needed volume of compost or soil is the same. Soil and compost bulk densities are assumed to be 1600 kg/m^3 and 400 kg/m^3 respectively. Thus, excavation of 4 Mg or 2.5 m^3 of soil is avoided per each Mg of compost used.

Compost from source separated biowaste substitute N, P, and K fertilizers. Mineral fertilizers production is modelled using ecoinvent processes "market for inorganic nitrogen fertiliser, as N – RU", "market for inorganic phosphorus fertiliser, as P2O5 – RU", "market for inorganic potassium fertiliser, as K2O – RU". Data taken from the ecoinvent database refer to the "allocation, cut-off by classification" system model.

2.6 Anaerobic digestion of organic fraction

Anaerobic digestion (AD) is only applied to the additional amount of organic waste which is separated according to the plan of the development of the system by 2024 (scenario 1), i.e. to source-separated organic fraction and screening reject from the new Gatchina and Kingisepp plants. Composition of screening reject used in AD is given in section 2.5.

Besides, AD process (“RoW: treatment of biowaste by anaerobic digestion”, cut-off system model) is applied only to organic part of waste subject to AD: contaminants are subtracted from the input flow.

Biogas combustion is modelled using unit process “RoW: heat and power co-generation, biogas, gas engine”, cut-off system model. Produced power and heat replace traditional production of power and heat in the region (see section 2.5.10 of the paper).

2.7 Recycling processes

Table S13. Data used in modelling of recycling processes

Process/parameter	Value	Unit	Reference
Paper and cardboard			
Recycling process	*tissue paper production, RoW*[1]		ecoinvent 3.7
Substituted process	*tissue paper production, virgin, GLO*		ecoinvent 3.7
Substitution ratio	0.83	$kg_{virgin\ paper}/kg_{recycled\ paper}$	[91]
PET recycling			
Recycling process	*polyethylene terephthalate production, granulate, amorphous, recycled, RoW*		ecoinvent 3.7
Substituted process	*polyethylene terephthalate production, granulate, amorphous, RoW*		ecoinvent 3.7
Substitution ratio	0.81	$kg_{virgin\ PET}/kg_{recycled\ PET}$	[92]
HDPE recycling			
Recycling process	*polyethylene production, high density, granulate, recycled, RoW*		ecoinvent 3.7
Substituted process	*polyethylene production, high density, granulate, RoW*		ecoinvent 3.7
Substitution ratio	0.75	$kg_{virgin\ HDPE}/kg_{recycled\ HDPE}$	[91]
Steel recycling			
Credit for recycled steel	*GLO: Value of scrap worldsteel*		GaBi database (2020.2)
Aluminium recycling			
Recycling process	*EU28+EFTA+Turkey: Aluminium remelting: wrought alloys ingot from scrap (2015) European Aluminium*		GaBi database (2020.2)
Substituted process	*GLO: Aluminium ingot mix IAI (2010) IAI*		GaBi database (2020.2)
Substitution process	*EU-15: Remelt aluminium ingots - credit (open loop)* (includes substitution ratio equal to 69%)		GaBi database (2020.2)
Glass recycling			
Recycling process			
water need	0.2	m^3/Mg_{cullet}	[60]
electricity need	551	kWh/Mg_{cullet}	[59]
heat consumption	6963	MJ/Mg_{cullet}	[59]
Substituted process	*packaging glass production, green, without cullet, GLO*		ecoinvent 3.7
Substitution ratio	1	$kg_{virgin\ glass}/kg_{recycled\ glass}$	[92]

[1] In this table and further italic text refers to unit processes from LCA software

2.8 Incineration of mixed MSW

Incineration process is modelled separately for several waste fractions using the following unit process from the GaBi database.

Table S14. Processes from GaBi (version 2020.2) used in modelling of mixed MSW incineration

Waste fraction	Unit process used
Biowaste	*EU-28: Waste incineration of biodegradable waste fraction in municipal solid waste (MSW) ELCD/CEWEP<p-agg>*
Paper and cardboard	*EU-28: Waste incineration of paper fraction in municipal solid waste (MSW) ELCD/CEWEP <p-agg>*
Metal	*EU-28: Waste incineration of ferro metals ELCD/CEWEP <p-agg>*
Plastic	*EU-28: Waste incineration of plastics (unspecified) fraction in municipal solid waste (MSW) ELCD/CEWEP <p-agg>*
Textile, leather, rubber	*EU-28: Waste incineration of textile fraction in municipal solid waste (MSW) ELCD/CEWEP <p-agg>*
Wood	*EU-28: Waste incineration of untreated wood (10.7% H2O content) ELCD/CEWEP<p-agg>*
Glass, inert waste, other waste[1]	*EU-28: Waste incineration of glass/inert material ELCD/CEWEP <p-agg>*

[1] Incineration of the “other waste” fraction received from the Leningrad region was modelled as if it is incineration of biowaste (50%) and textile (50%). Incineration of the “other waste” fraction received from Saint Petersburg was modelled as glass/inert material incineration.

2.9 RDF incineration

Table S15. Composition of RDF and characteristics of RDF fractions

Waste fraction	Content in RDF, %	Moisture content, %	Carbon content, %		Fossil carbon content, %	
			of TS	of waste	of C	of waste
Paper, cardboard	42.7	10	43	39	0	0
Plastics	33.6	1	59	58	100	58
Liquid packaging board	5.5	1[1]	12[2]	12	100	12
Textile	10.2	10	56	50	50	25
Leather	3.2	5[3]	51[3]	48	50[4]	24
Rubber		0[3]	65[3]	65	50[4]	33
Wood	4.8	1	50	49	0	0
Reference	[46]	[93,94] if no other reference				

[1] Assumed equal to moisture content of plastic
[2] Assuming that plastic content in Tetra Pak equals 20%
[3] Values from [95]
[4] Assumed value

The report on municipal solid waste incineration plants shows that the most common practice of bottom and fly ashes handling in Russia is landfill disposal (both MSW and hazardous waste landfill are applied depending on the toxicity of residues) [96]. Therefore, in this study landfill disposal of bottom ash and fly ash are modelled.

Table S16. LCI data on RDF incineration

Parameter	Value	Unit	Reference
LHV of RDF	15.9 [1]	MJ/kg_{RDF}	[61]
Bottom ash output	15.7 [1]	% of RDF	[61]
Fly ash output	4	% of RDF	[97]
Ashes disposal	*EU-28: Inert matter (Glass) on landfill*		GaBi database (2020.2)
Emissions from RDF incineration before treatment			
CO_2	861	g/kg_{RDF}	Calculated based on Table S15
NO_x	2.3	g/kg_{RDF}	[44]
SO_2	1.7	g/kg_{RDF}	[44]
RDF utilization in a cement kiln			
LHV of coal	22.5	MJ/kg	[98]
coal acquisition	*RU: Hard coal mix*		GaBi database (2020.2)
coal combustion	*RU: Process steam from hard coal 95%*		GaBi database (2020.2)
RDF utilization in a boiler			
natural gas need (auxiliary fuel)	1.9	m^3/Mg_{RDF}	[99]
natural gas supply	*FI: Natural gas mix*		GaBi database (2020.2)
electricity production efficiency	22	%	[62]

[1] Averaged from the given interval

Table S17. LCI data on flue gases treatment process

Parameter	Value	Unit	Reference
Lime consumption of a scrubber	6	g/kg_{RDF}	[99]
Lime supply	*DE: Calcium hydroxide (Ca(OH)2; dry; slaked lime) (EN15804 A1-A3)*		GaBi database (2020.2)
NH_3 consumption of SNCR unit	2.75	g/kg_{RDF}	[99]
Ammonia supply	*EU-28: Ammonia (NH3) production mix, without CO2 recovery*		GaBi database (2020.2)
Water consumption of APC	0.5	dm^3/kg_{RDF}	[99]
Water supply	*EU-28: Process water*		GaBi database (2020.2)
NO_x emission reduction	50	%	[100]
SO_2 emission reduction	50	%	[101]
APC residues amount	5	% RDF input	[99]

3 Sensitivity analysis

3.1 Perturbation analysis

Normalized sensitivity ratios (NSR) are obtained following the approach described by Starostina et al. [27]. For each impact category, sensitivity ratios (SR) are normalized over the largest SR score among the scenarios so that the NSRs range between 0 and 1. NSR is calculated using the equation:

$$NSR_i^j = \frac{\left|SR_i^j\right|}{max\left(SR_i^j\right)^j},$$

where i is a parameter, and j is an impact category. Thus, in a specific scenario and impact category, NSR values that are close to 1 represent parameters to which the LCIA results are most sensitive. NSR values are further weighted and aggregated among impact categories to identify the parameters that most affect the performance of the studied system.

Normalized sensitivity ratio values are further weighted and summed up among impact categories to identify parameters which affect the overall performance of the studied system the most. NSR are weighted according to the rules stated in Table S18. Weighted NSR values for each impact category is then aggregated so that overall values are obtained for each parameter in each scenario.

Table S18. Weighting rules for NSR in perturbation analysis

Original NSR value	Weighted NSR value
<0.5	0
0.5<NSR<0.8	0.8
0.8<NSR<0.9	0.9
0.9<NSR<1	1

Perturbation analysis was performed for 8 parameters presented in Table S19. The results of perturbation analysis are presented further in Sections 4.1 and 4.2.

Table S19. Parameters checked in perturbation analysis

Parameter	Initial value
LFG collection rate	53%
Leachate generation	0.2 g/g_{MSW}
Electric efficiency of RDF combustion	22%
LHV of RDF	15.9 MJ/kg_{RDF}
Recovery rate of source separated metal at sorting plant	100%
Recovery rate of source separated glass at sorting plant	98%
Recovery rate of source separated plastic at sorting plant	100%
Recovery rate of source separated paper and cardboard at sorting plant	100%

3.2 Impact of modelling choices: alternative data

Alternative MSW composition represents a weighted average data considering the population and composition of MSW from Kirovsky, Lomonosovsky and Tosnensky districts of Leningrad region.

Table S20. Alternative data on MSW composition in Leningrad region [40]

Organic waste, %	28.0
Paper and cardboard, %	20.2
Non-ferrous metals, %	1.0
Ferrous metals, %	3.3
Glass, %	11.7
Plastics, %	6.4
Leather, rubber, %	2.3
Textile, %	7.2
Wood, %	3.5
Inert materials, %	3.2
Other materials, %	13.2

4 Results

4.1 Perturbation analysis: sensitivity ratios

Table S21. Sensitivity ratios of parameters in each scenario, GWP impact category

	S0	S1	S2	S3	S4.1	S4.2
LFG collection rate	-0.22	-0.28	-0.76	-1.50	-7.57	64.75
Leachate generation	0.00	0.00	0.00	0.00	0.00	0.00
Electric eff. of RDF combustion	-0.04	-0.14	-0.19	-0.44	-1.95	16.69
LHV of RDF	0.00	-0.08	-0.11	-0.26	-1.15	9.83
Recovery rate, metal	0.00	0.00	0.00	0.00	-0.51	4.36
Recovery rate, glass	0.00	0.00	0.00	0.00	-1.59	13.62
Recovery rate, plastic	0.00	0.00	0.00	0.00	-4.18	35.73
Recovery rate, paper&cardboard	0.00	0.00	0.00	0.00	-1.87	16.01

Table S22. Sensitivity ratios of parameters in each scenario, EP impact category

	S0	S1	S2	S3	S4.1	S4.2
LFG collection rate	0.22	0.14	0.24	0.60	-0.04	-0.03
Leachate generation	0.23	0.12	0.11	0.21	-0.01	-0.01
Electric eff. of RDF combustion	-0.29	-0.54	-0.47	-1.38	0.07	0.06
LHV of RDF	0.00	-0.35	-0.31	-0.90	0.05	0.04
Recovery rate, metal	0.00	0.00	0.00	0.00	0.00	0.00
Recovery rate, glass	0.00	0.00	0.00	0.00	0.04	0.03
Recovery rate, plastic	0.00	0.00	0.00	0.00	0.97	0.75
Recovery rate, paper&cardboard	0.00	0.00	0.00	0.00	0.37	0.28

Table S23. Sensitivity ratios of parameters in each scenario, AP impact category

	S0	S1	S2	S3	S4.1	S4.2
LFG collection rate	1.13	-0.84	-10.22	0.09	0.03	0.02
Leachate generation	0.00	0.00	0.00	0.00	0.00	0.00
Electric eff. of RDF combustion	15.97	-20.92	-127.83	1.28	0.42	0.31
LHV of RDF	0.00	-8.92	-54.48	0.55	0.18	0.13
Recovery rate, metal	0.00	0.00	0.00	0.00	0.02	0.01
Recovery rate, glass	0.00	0.00	0.00	0.00	0.06	0.04
Recovery rate, plastic	0.00	0.00	0.00	0.00	0.66	0.49
Recovery rate, paper&cardboard	0.00	0.00	0.00	0.00	0.46	0.35

Table S24. Sensitivity ratios of parameters in each scenario, ADP_f impact category

	S0	S1	S2	S3	S4.1	S4.2
LFG collection rate	0.24	0.08	0.14	0.05	0.07	0.06
Leachate generation	0.00	0.00	0.00	0.00	0.00	0.00
Electric eff. of RDF combustion	0.59	0.52	0.49	0.19	0.24	0.21
LHV of RDF	0.00	0.33	0.31	0.12	0.15	0.13
Recovery rate, metal	0.00	0.00	0.00	0.00	0.04	0.04
Recovery rate, glass	0.00	0.00	0.00	0.00	0.27	0.24
Recovery rate, plastic	0.00	0.00	0.00	0.00	0.18	0.15
Recovery rate, paper&cardboard	0.00	0.00	0.00	0.00	0.06	0.05

4.2 Perturbation analysis: normalized sensitivity ratios

Table S25. Normalized sensitivity ratios of parameters in each scenario, GWP impact category

	S0	S1	S2	S3	S4.1	S4.2
LFG collection rate	0.00	0.00	0.01	0.02	0.12	1.00
Leachate generation	-	-	-	-	-	-
Electric eff. of RDF combustion	0.00	0.01	0.01	0.03	0.12	1.00
LHV of RDF	0.00	0.01	0.01	0.03	0.12	1.00
Recovery rate, metal	0.00	0.00	0.00	0.00	0.12	1.00
Recovery rate, glass	0.00	0.00	0.00	0.00	0.12	1.00
Recovery rate, plastic	0.00	0.00	0.00	0.00	0.12	1.00
Recovery rate, paper&cardboard	0.00	0.00	0.00	0.00	0.12	1.00

Table S26. Normalized sensitivity ratios of parameters in each scenario, EP impact category

	S0	S1	S2	S3	S4.1	S4.2
LFG collection rate	0.36	0.23	0.40	1.00	0.06	0.05
Leachate generation	1.00	0.55	0.48	0.91	0.06	0.04
Electric eff. of RDF combustion	0.21	0.39	0.34	1.00	0.05	0.04
LHV of RDF	0.00	0.39	0.34	1.00	0.05	0.04
Recovery rate, metal	0.00	0.00	0.00	0.00	1.00	0.78
Recovery rate, glass	0.00	0.00	0.00	0.00	1.00	0.78
Recovery rate, plastic	0.00	0.00	0.00	0.00	1.00	0.78
Recovery rate, paper&cardboard	0.00	0.00	0.00	0.00	1.00	0.78

Table S27. Normalized sensitivity ratios of parameters in each scenario, AP impact category

	S0	S1	S2	S3	S4.1	S4.2
LFG collection rate	0.11	0.08	1.00	0.01	0.00	0.00
Leachate generation	-	-	-	-	-	-
Electric eff. of RDF combustion	0.12	0.16	1.00	0.01	0.00	0.00
LHV of RDF	0.00	0.16	1.00	0.01	0.00	0.00
Recovery rate, metal	0.00	0.00	0.00	0.00	1.00	0.75
Recovery rate, glass	0.00	0.00	0.00	0.00	1.00	0.75
Recovery rate, plastic	0.00	0.00	0.00	0.00	1.00	0.75
Recovery rate, paper&cardboard	0.00	0.00	0.00	0.00	1.00	0.75

Table S28. Normalized sensitivity ratios of parameters in each scenario, ADP_f impact category

	S0	S1	S2	S3	S4.1	S4.2
LFG collection rate	1.00	0.31	0.58	0.19	0.28	0.24
Leachate generation	-	-	-	-	-	-
Electric eff. of RDF combustion	1.00	0.88	0.82	0.32	0.40	0.35
LHV of RDF	0.00	1.00	0.93	0.36	0.46	0.39
Recovery rate, metal	0.00	0.00	0.00	0.00	1.00	0.86
Recovery rate, glass	0.00	0.00	0.00	0.00	1.00	0.86
Recovery rate, plastic	0.00	0.00	0.00	0.00	1.00	0.86
Recovery rate, paper&cardboard	0.00	0.00	0.00	0.00	1.00	0.86

Table S29. Aggregated weighted results of perturbation analysis over all impact categories. For each impact category, NSR is weighted as 0 when NSR<0.5, 0.8 when 0.5<NSR<0.8, 0.9 when 0.8<NSR<0.9 and 1 when 0.9<NSR<1

	S0	S1	S2	S3	S4.1	S4.2
LFG collection rate	1	0	1.8	1	0	1
Leachate generation	1	0.8	0	1	0	0
RDF LHV	1	0.9	1.9	1	0	1
RDF electric efficiency	0	1	2	1	0	1
Recovery rate[1], metal	0	0	0	0	3	3.5
Recovery rate[1], plastic	0	0	0	0	3	3.5
Recovery rate[1], paper, cardboard	0	0	0	0	3	3.5
Recovery rate[1], glass	0	0	0	0	3	3.5

[1] Recovery rates related to separation of source separated materials (S4)

According to the results, GWP has shown significant sensitivity to LFG collection rate in all scenarios. In scenario S0, GWP changes by 22% with 10% of LFG collection rate. As this study uses secondary data for this parameter, the magnitude of GWP may change substantially with the adoption of site-specific data. However, changes in scenario ranking are not expected since the parameter influences all scenarios. LHV of RDF appeared to be an important parameter that affects AP and ADP_f the most. This parameter is also present in all scenarios so it can only affect the magnitude of impact scores. Lastly, the results are sensitive to the recovery rate of separately collected paper and cardboard fraction. Environmental impacts of scenario S4 may rise substantially with the decrease of the parameter.

4.3 Specific net impact potentials of processes involved in MSW management

Table S30. Specific net impact potentials of processes for GWP, kg CO_2-eq per kg of MSW handled in a relevant process

	S0	S1	S2	S3	S4.1	S4.2
Collection, transportation	0.01	0.01	0.01	0.01	0.01	0.01
Waste sorting	0.01	0.02	0.02	0.02	0.01	0.01
Landfilling	0.37	0.35	0.25	0.18	0.20	0.20
Steel recycling	-1.62	-1.62	-1.62	-1.62	-1.62	-1.62
Aluminium recycling	-10.4	-10.4	-10.4	-10.4	-10.4	-10.4
Plastic recycling	-1.69	-1.69	-1.69	-1.69	-1.69	-1.69
Glass recycling	-0.42	-0.42	-0.42	-0.42	-0.42	-0.42
Paper and cardboard recycling	-1.14	-1.14	-1.14	-1.14	-1.14	-1.14
Composting	0.06	0.06	0.06	0.06	0.06	0.03
Anaerobic digestion	-	-	-	-	-	-0.11
RDF combustion	-0.92	0.15	0.15	0.15	0.15	0.15
Incineration	-0.09	-0.09	-0.09	-0.01	-0.10	-0.10

Table S31. Specific net impact potentials of processes for EP, kg PO_4^{3-}-eq per kg of MSW handled in a relevant process

	S0	S1	S2	S3	S4.1	S4.2
Collection, transportation	0.000003	0.000003	0.000003	0.000003	0.000004	0.000004
Waste sorting	0.000005	0.000007	0.000007	0.000007	0.000005	0.000005
Landfilling	0.000006	0.000007	0.000010	0.000012	0.000012	0.000012
Steel recycling	-0.000134	-0.000134	-0.000134	-0.000134	-0.000134	-0.000134
Aluminium recycling	-0.004512	-0.004512	-0.004512	-0.004512	-0.004512	-0.004512
Plastic recycling	-0.000422	-0.000422	-0.000422	-0.000422	-0.000422	-0.000422
Glass recycling	-0.001006	-0.001006	-0.001006	-0.001006	-0.001006	-0.001006
Paper and cardboard recycling	-0.003728	-0.003728	-0.003728	-0.003728	-0.003728	-0.003728
Composting	0.000392	0.000371	0.000371	0.000371	0.000395	0.000169
Anaerobic digestion	-	-	-	-	-	-0.000035
RDF combustion	-0.000333	-0.000101	-0.000101	-0.000101	-0.000101	-0.000101

Incineration	-0.000048	-0.000048	-0.000048	-0.000047	-0.000051	-0.000051

Table S32. Specific net impact potentials of processes for AP, kg SO_2-eq per kg of MSW handled in a relevant process

	S0	S1	S2	S3	S4.1	S4.2
Collection, transportation	0.00001	0.00001	0.00001	0.00001	0.00002	0.00002
Waste sorting	0.00008	0.00012	0.00012	0.00012	0.00009	0.00009
Landfilling	0.00009	0.00011	0.00009	0.00015	0.00012	0.00012
Steel recycling	-0.00256	-0.00256	-0.00256	-0.00256	-0.00256	-0.00256
Aluminium recycling	-0.07041	-0.07041	-0.07041	-0.07041	-0.07041	-0.07041
Plastic recycling	-0.00259	-0.00259	-0.00259	-0.00259	-0.00259	-0.00259
Glass recycling	-0.00595	-0.00595	-0.00595	-0.00595	-0.00595	-0.00595
Paper recycling	-0.01203	-0.01203	-0.01203	-0.01203	-0.01203	-0.01203
Composting	0.00182	0.00168	0.00168	0.00168	0.00178	0.00077
Anaerobic digestion	-	-	-	-	-	-0.00039
RDF combustion	-0.01865	-0.00413	-0.00413	-0.00413	-0.00413	-0.00413
Incineration	-0.00099	-0.00099	-0.00099	-0.00084	-0.00106	-0.00106

Table S33. Specific net impact potentials of processes for ADP_f, MJ per kg of MSW handled in a relevant process

	S0	S1	S2	S3	S4.1	S4.2
Collection, transportation	0.09	0.08	0.08	0.08	0.12	0.12
Waste sorting	0.21	0.29	0.29	0.29	0.21	0.21
Landfilling	-0.07	-0.08	-0.16	-0.21	-0.20	-0.20
Steel recycling	-15.5	-15.5	-15.5	-15.5	-15.5	-15.5
Aluminium recycling	-97.1	-97.1	-97.1	-97.1	-97.1	-97.1
Plastic recycling	-35.0	-35.0	-35.0	-35.0	-35.0	-35.0
Glass recycling	-2.00	-2.00	-2.00	-2.00	-2.00	-2.00
Paper recycling	-9.46	-9.46	-9.46	-9.46	-9.46	-9.46
Composting	0.31	0.22	0.22	0.22	0.21	0.12
Anaerobic digestion	-	-	-	-	-	-1.03
RDF combustion	-20.7	-9.43	-9.43	-9.43	-9.43	-9.43

Incineration	-6.71	-6.71	-6.71	-5.56	-7.26	-7.26

4.4 Life cycle impact assessment results

Table S34. LCIA results in processes for GWP, kg CO_2-eq/a

	S0	S1	S2	S3	S4.1	S4.2
Collection, transportation	1.95E+07	1.79E+07	1.79E+07	1.78E+07	2.56E+07	2.56E+07
Waste sorting	7.99E+06	2.71E+07	2.71E+07	2.71E+07	3.11E+07	3.11E+07
Landfilling	1.05E+09	8.38E+08	6.16E+08	2.91E+08	3.75E+08	3.75E+08
Steel recycling	-8.31E+06	-2.80E+07	-2.80E+07	-2.80E+07	-4.87E+07	-4.87E+07
Aluminium recycling	-1.70E+06	-5.53E+06	-5.53E+06	-5.53E+06	-2.19E+07	-2.19E+07
Plastic recycling	-1.86E+07	-6.17E+07	-6.17E+07	-6.17E+07	-1.33E+08	-1.33E+08
Glass recycling	-1.03E+06	-2.16E+06	-2.16E+06	-2.16E+06	-6.98E+07	-6.98E+07
Paper recycling	-8.00E+06	-2.59E+07	-2.59E+07	-2.59E+07	-1.50E+08	-1.50E+08
Composting	8.53E+06	2.27E+07	2.27E+07	2.27E+07	3.45E+07	1.73E+07
Anaerobic digestion	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-1.62E+04
RDF combustion	-2.31E+07	2.21E+07	2.21E+07	2.21E+07	2.21E+07	2.21E+07
Incineration	-5.84E+05	-5.84E+05	-5.84E+05	-5.85E+06	-6.52E+05	-6.52E+05

Table S35. LCIA results in processes for EP, kg PO_4^{3-}-eq/a

	S0	S1	S2	S3	S4.1	S4.2
Collection, transportation	1.02E+04	9.39E+03	9.39E+03	9.33E+03	1.34E+04	1.34E+04
Waste sorting	2.62E+03	8.88E+03	8.88E+03	8.88E+03	1.02E+04	1.02E+04
Landfilling	1.73E+04	1.60E+04	2.43E+04	1.92E+04	2.20E+04	2.20E+04
Steel recycling	-6.85E+02	-2.31E+03	-2.31E+03	-2.31E+03	-4.01E+03	-4.01E+03
Aluminium recycling	-7.36E+02	-2.39E+03	-2.39E+03	-2.39E+03	-9.49E+03	-9.49E+03
Plastic recycling	-4.66E+03	-1.54E+04	-1.54E+04	-1.54E+04	-3.33E+04	-3.33E+04
Glass recycling	-2.49E+03	-5.24E+03	-5.24E+03	-5.24E+03	-1.69E+05	-1.69E+05
Paper recycling	-2.62E+04	-8.48E+04	-8.48E+04	-8.48E+04	-4.93E+05	-4.93E+05
Composting	5.23E+04	1.52E+05	1.52E+05	1.52E+05	2.35E+05	1.11E+05

Anaerobic digestion	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-1.62E+04
RDF combustion	-8.33E+03	-1.52E+04	-1.52E+04	-1.52E+04	-1.52E+04	-1.52E+04
Incineration	-3.11E+02	-3.11E+02	-3.11E+02	-4.02E+04	-3.27E+02	-3.27E+02

Table S36. LCIA results in processes for AP, kg SO_2-eq/a

	S0	S1	S2	S3	S4.1	S4.2
Collection, transportation	4.44E+04	4.07E+04	4.07E+04	4.05E+04	5.82E+04	5.82E+04
Waste sorting	4.70E+04	1.60E+05	1.60E+05	1.60E+05	1.83E+05	1.83E+05
Landfilling	2.58E+05	2.61E+05	2.25E+05	2.36E+05	2.28E+05	2.28E+05
Steel recycling	-1.31E+04	-4.40E+04	-4.40E+04	-4.40E+04	-7.67E+04	-7.67E+04
Aluminium recycling	-1.15E+04	-3.74E+04	-3.74E+04	-3.74E+04	-1.48E+05	-1.48E+05
Plastic recycling	-2.86E+04	-9.48E+04	-9.48E+04	-9.48E+04	-2.05E+05	-2.05E+05
Glass recycling	-1.47E+04	-3.10E+04	-3.10E+04	-3.10E+04	-1.00E+06	-1.00E+06
Paper recycling	-8.45E+04	-2.74E+05	-2.74E+05	-2.74E+05	-1.59E+06	-1.59E+06
Composting	2.43E+05	6.88E+05	6.88E+05	6.88E+05	1.06E+06	5.04E+05
Anaerobic digestion	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-1.83E+05
RDF combustion	-4.66E+05	-6.20E+05	-6.20E+05	-6.20E+05	-6.20E+05	-6.20E+05
Incineration	-6.35E+03	-6.35E+03	-6.35E+03	-7.18E+05	-6.77E+03	-6.77E+03

Table S37. LCIA results in processes for ADP_f, MJ/a

	S0	S1	S2	S3	S4.1	S4.2
Collection, transportation	2.75E+08	2.51E+08	2.51E+08	2.50E+08	3.60E+08	3.60E+08
Waste sorting	1.14E+08	3.86E+08	3.86E+08	3.86E+08	4.43E+08	4.43E+08
Landfilling	-1.92E+08	-1.86E+08	-3.94E+08	-3.38E+08	-3.81E+08	-3.81E+08
Steel recycling	-7.96E+07	-2.68E+08	-2.68E+08	-2.68E+08	-4.66E+08	-4.66E+08
Aluminium recycling	-1.58E+07	-5.15E+07	-5.15E+07	-5.15E+07	-2.04E+08	-2.04E+08
Plastic recycling	-3.87E+08	-1.28E+09	-1.28E+09	-1.28E+09	-2.77E+09	-2.77E+09
Glass recycling	-4.96E+06	-1.04E+07	-1.04E+07	-1.04E+07	-3.37E+08	-3.37E+08
Paper recycling	-6.64E+07	-2.15E+08	-2.15E+08	-2.15E+08	-1.25E+09	-1.25E+09
Composting	4.09E+07	8.86E+07	8.86E+07	8.86E+07	1.27E+08	7.52E+07

Anaerobic digestion	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-4.76E+08
RDF combustion	-5.18E+08	-1.41E+09	-1.41E+09	-1.41E+09	-1.41E+09	-1.41E+09
Incineration	-4.31E+07	-4.31E+07	-4.31E+07	-4.76E+09	-4.66E+07	-4.66E+07

References

1. Ministry of Natural Resources and the Environment of the Russian Federation Passport of the National Project “Ecology” [Pasport Natsional’nogo Proyekta «Ekologiya»] Available online: http://www.mnr.gov.ru/activity/directions/natsionalnyy_proekt_ekologiya/ (accessed on Jul 1, 2020).

2. Waste Management Committee of the Leningrad Region Territorial Scheme for Waste Managament, including Municipal Solid Waste Management [Territorial’naya skhema obrashcheniya s otkhodami, v tom chisle s tverdymi kommunal’nymi otkhodami] Available online: https://waste.lenobl.ru/ru/deiatelnost/tershema/ (accessed on Jul 2, 2020).

3. Committee for the Improvement of Saint Petersburg Territorial production and consumption waste management scheme [Territorialnaya skhema obrashchenya s othodami proizvodstva i potrebleniya] Available online: https://www.gov.spb.ru/gov/otrasl/blago/documents/new_npa/ (accessed on Jun 25, 2020).

4. Administration of St. Petersburg Conclusion dated 17.02.2020 No. 01-12-6 20-0-0 [Заключение от 17.02.2020 № 01-12-6 20-0-0] Available online: https://www.gov.spb.ru/gov/otrasl/blago/documents/obshestvennoe-obsuzhdenie-proektov-normativnyh-pravovyh-aktov/zaklyuchenie-ot-17022020-01-12-6-20-0-0/ (accessed on Feb 17, 2021).

5. IPCC CH4 Emissions from Solid Waste Disposal. *IPCC Good Pract. Guid. Uncertain. Manag. Natl. Greenh. Gas Invent.* **2006**, 419–439.

6. Havukainen, J.; Zhan, M.; Dong, J.; Liikanen, M.; Deviatkin, I.; Li, X.; Horttanainen, M. Environmental impact assessment of municipal solid waste management incorporating mechanical treatment of waste and incineration in Hangzhou, China. *J.*

Clean. Prod. **2017**, *141*, 453–461, doi:10.1016/j.jclepro.2016.09.146.

7. Liikanen, M.; Havukainen, J.; Viana, E.; Horttanainen, M. Steps towards more environmentally sustainable municipal solid waste management – A life cycle assessment study of São Paulo, Brazil. *J. Clean. Prod.* **2018**, *196*, 150–162, doi:10.1016/j.jclepro.2018.06.005.

8. LIPASTO Average emissions and energy use of working machines per fuel in Finland in 2016 Available online: http://lipasto.vtt.fi/yksikkopaastot/indexe.htm (accessed on Jul 21, 2020).

9. IPCC Guidelines for National Greenhouse Gas Inventories. Volume 5. Waste Available online: https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol5.html (accessed on Nov 5, 2020).

10. Lee, U.; Han, J.; Wang, M. Evaluation of landfill gas emissions from municipal solid waste landfills for the life-cycle analysis of waste-to-energy pathways. *J. Clean. Prod.* **2017**, *166*, 335–342, doi:10.1016/j.jclepro.2017.08.016.

11. Doka, G. Landfills. Underground Deposits. Landfarming Available online: https://www.doka.ch/13_III_Landfills.pdf (accessed on Nov 5, 2020).

12. Bacchi, D.; Bacci, R.; Ferrara, G.; Lombardi, L.; Pecorini, I.; Rossi, E. Life Cycle Assessment (LCA) of landfill gas management: Comparison between conventional technologies and microbial oxidation systems. *Energy Procedia* **2018**, *148*, 1066–1073, doi:10.1016/j.egypro.2018.08.053.

13. MPBO-2 Investment program of the St. Petersburg State Unitary Enterprise “Plant for mechanized processing of household waste” in the field of solid waste management for 2019-2023 [Investitsionnaya programma Sankt-Peterburgskogo gosudarstvennogo unitarnogo predpr Available online: https://mpbo2.ru/standarty-raskrytiya-informacii-dok/ (accessed on Sep 23, 2020).

14. OOO "KOSMOS " Correction of the project "Landfill for solid household and construction waste in the village of M. Zamostye, Gatchina district Leningrad region " [Korrektirovka proyekta "Poligon tverdykh bytovykh i stroitel’nykh otkhodov v d. M.Zamostje Gatchinskogo rai Available online: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwi85MyftbrtAhXBAxAIHYitCx8QFjAAegQIAxAC&url=http%3A%2F%2Fradm.gtn.ru%2F_file%2Fnews%2F323abe34eba78b10333e3bac779180c2.doc&usg=AOvVaw2drnFzsr9QsJAsc6TZKGDu (accessed on Jul 12, 2020).

15. AO "Avtopark №1 "Spetstrans " Interview data and data received afterwards on 21.09.2021 2021.

16. Rospotrebnadzor The register of sanitary and epidemiological conclusions on the compliance (non-compliance) of activities (works, services) with the requirements of state sanitary and epidemiological rules and regulations [Reyestr sanitarno-epidemiologicheskikh zaklyuche Available online: http://fp.crc.ru/service/?oper=s&uinz=%29F%29%28%2CJNc4fM&pdk=on&pril=on (accessed on Mar 9, 2020).

17. Federal Department of State statistics Database of indicators of municipalities [Baza dannykh pokazateley munutsipalnykh obrazavaniy] Available online: https://rosstat.gov.ru/dbscripts/munst/munst41/DBInet.cgi (accessed on Jun 14, 2020).

18. Nasrullah, M.; Vainikka, P.; Hannula, J.; Hurme, M.; Kärki, J. Mass, energy and material balances of SRF production process. Part 3: Solid recovered fuel produced from municipal solid waste. *Waste Manag. Res.* **2015**, *33*, 146–156, doi:10.1177/0734242X14563375.

19. Pressley, P.N.; Levis, J.W.; Damgaard, A.; Barlaz, M.A.; DeCarolis, J.F. Analysis of material recovery facilities for use in life-cycle assessment. *Waste Manag.* **2015**, *35*, 307–317, doi:10.1016/j.wasman.2014.09.012.

20. Il'inykh, G.V.; Ustyantsev, E.A.; Vaisman, Y.I. Construction of the material balance of the line for manual sorting of solid household waste [Postroyeniye material'nogo balansa linii ruchnoy sortirovki tverdykh bytovykh otkhodov]. **2013**, 22–25, doi:10.18412/1816-0395-2013-1-22-25.

21. Lima, P.D.M.; Colvero, D.A.; Gomes, A.P.; Wenzel, H.; Schalch, V.; Cimpan, C. Environmental assessment of existing and alternative options for management of municipal solid waste in Brazil. *Waste Manag.* **2018**, *78*, 857–870, doi:10.1016/j.wasman.2018.07.007.

22. AO "DAR/VODGEO " Construction of a complex for the processing and disposal of St. Petersburg waste in the Lyubanskoye forestry of the Tosnensky municipal district of the Leningrad region. Project documentation. Environmental impact assessment Available online: http://www.infoeco.ru/assets/images/poligon/233-OBOC.pdf (accessed on Jun 13, 2020).

23. Grzesik, K.; Malinowski, M. Life Cycle Assessment of Mechanical-Biological Treatment of Mixed Municipal Waste. *Environ. Eng. Sci.* **2017**, *34*, 207–220, doi:10.1089/ees.2016.0284.

24. Boldrin, A.; Andersen, J.K.; Møller, J.; Christensen, T.H.; Favoino, E. Composting and compost utilization: Accounting of greenhouse gases and global warming contributions. *Waste Manag. Res.* **2009**, *27*, 800–812, doi:10.1177/0734242X09345275.

25. Ham, R.K.; Komilis, D. A Laboratory Study to Investigate Gaseous Emissions and Solids Decomposition During Composting of Municipal Solid Waste. **2003**, 149.

26. Di Lonardo, M.C.; Lombardi, F.; Gavasci, R. Characterization of MBT plants input and outputs: A review. *Rev. Environ. Sci. Biotechnol.* **2012**, *11*, 353–363, doi:10.1007/s11157-012-9299-2.

27. Gala, A.B.; Raugei, M.; Fullana-i-Palmer, P. Introducing a new method for calculating

the environmental credits of end-of-life material recovery in attributional LCA. *Int. J. Life Cycle Assess.* **2015**, *20*, 645–654, doi:10.1007/s11367-015-0861-3.

28. Rigamonti, L.; Grosso, M.; Giugliano, M. Life cycle assessment of sub-units composing a MSW management system. *J. Clean. Prod.* **2010**, *18*, 1652–1662, doi:10.1016/j.jclepro.2010.06.029.

29. Landi, D.; Germani, M.; Marconi, M. Analyzing the environmental sustainability of glass bottles reuse in an Italian wine consortium. In Proceedings of the Procedia CIRP; Elsevier B.V., 2019; Vol. 80, pp. 399–404.

30. Greene, J. Energy implications of glass-container recycling. *Hosp. Heal. Networks* **2007**, *81*, 65–69, doi:10.12968/sece.2008.6.1230.

31. Finnveden, G.; Johansson, J.; Lind, P.; Moberg, Å. Life Cycle Assessments of Energy from Solid Waste Available online: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.197.4254&rep=rep1&type=pdf (accessed on Nov 26, 2020).

32. Bjarnadóttir, H.J.; Friðriksson, G.B.; Johnsen, T.; Sletsen, H. Guidelines for the use of LCA in the waste management sector Available online: http://www.nordtest.org/register/techn/tlibrary/tec517/tec517.pdf (accessed on Nov 6, 2020).

33. Larionov, K.B.; Tsibulskiy, S.A.; Slyusarskiz, K. V.; Tolokolnikov, A.A.; Gubin, V.E. Study of the physical-chemical characteristics of non-food solid waste combustion. *J. Phys. Conf. Ser.* **2019**, *1359*, doi:10.1088/1742-6596/1359/1/012065.

34. EkoSPES Waste incineration plants and incinerators in the Russian Federation [Musoroszhigatel’nyye zavody i insineratory v Rossiyskoy Federatsii] Available online: http://www.ecoaccord.org/news2020/Обзор 15.06.2020.pdf (accessed on Aug 24, 2020).

35. Bushikhin, V.V.; Lomtev, A.Y.; Budko, A.G.; Pakhtinov, V.. Alternative fuel from solid household waste [Alternativnoe toplivo iz tverdikh bitovikh otkhodov] Available online: http://www.atr-sz.ru/files/visual/2015_04_29/alt_fuel.pdf (accessed on Oct 2, 2020).

36. Consonni, S.; Giugliano, M.; Grosso, M. Alternative strategies for energy recovery from municipal solid waste: Part A: Mass and energy balances. In Proceedings of the Waste Management; Elsevier Ltd, 2005; Vol. 25, pp. 123–135.

37. Małkowski, P. The quality of coal in Poland, Russia and Ukraine and its effect on dust emission into the atmosphere during combustion. *Czas. Tech.* **2018**, *9*, 141–161, doi:10.4467/2353737xct.18.138.8977.

38. Astrup, T.; Møller, J.; Fruergaard, T. Incineration and co-combustion of waste: Accounting of greenhouse gases and global warming contributions. *Waste Manag. Res.* **2009**, *27*, 789–799, doi:10.1177/0734242X09343774.

39. Kourkoumpas, D.S.; Karellas, S.; Kouloumoundras, S.; Koufodimos, G.; Grammelis, P.; Kakaras, E. Comparison of waste-to-energy processes by means of life cycle analysis principles regarding the global warming potential impact: Applied case studies in greece, france and germany. *Waste and Biomass Valorization* **2015**, *6*, 605–621, doi:10.1007/s12649-015-9367-2.

40. Zandaryaa, S.; Gavasci, R.; Lombardi, F.; Fiore, A. Nitrogen oxides from waste incineration: Control by selective non-catalytic reduction. In Proceedings of the Chemosphere; Pergamon, 2001; Vol. 42, pp. 491–497.

41. Liu, Z.S. Advanced experimental analysis of the reaction of Ca(OH)2 with HCl and SO2 during the spray dry scrubbing process. *Fuel* **2005**, *84*, 5–11, doi:10.1016/j.fuel.2004.07.004.

42. Starostina, V.; Damgaard, A.; Eriksen, M.K.; Christensen, T.H. Waste management in the Irkutsk region, Siberia, Russia: An environmental assessment of alternative

development scenarios. *Waste Manag. Res.* **2018**, *36*, 373–385, doi:10.1177/0734242X18757627.