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CURRENT STATE AND POSSIBLE DEVELOPMENTS OF MUNICIPAL SOLID WASTE MANAGEMENT SYSTEM IN THE LENINGRAD REGION AND SAINT PETERSBURG: A LIFE CYCLE ASSESSMENT

Examiners:	Professor, D.Sc. (Tech.) Mika Horttanainen
	Associate Professor, D.Sc. (Tech) Jouni Havukainen

ABSTRACT

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Waste management in Saint Petersburg and the surrounding Leningrad region is based on landfilling nowadays. Municipal solid waste is normally collected by a one-bin system. Around 10-20% of collected waste is sorted at the sorting stations to recover recyclable materials. Additionally, at some stations, composting of a screening reject is applied to produce a landfill cover material. Such a system results in a vast amount of waste degrading in the landfills instead of being used as a resource. Also, this way of handling waste is greenhouse gas-intensive. These concerns, coupled with the growing amount of generated waste, led to the reformation of the waste management system in the area which is currently underway. To help the reformation succeed, this thesis provides the evaluation of the environmental performance of the municipal solid waste management system in the area through a life cycle assessment. The evaluation is conducted for several scenarios, including the current state of the system and the state that should be reached by 2024 aided by the reformation. Furthermore, the effects of proposed improvements are evaluated in separate scenarios. The impact is assessed in terms of climate change, acidification, eutrophication, and resource depletion (fossil fuels).

The overall reduction of the environmental impact is seen as the system develops, and it is mostly reached via avoided production. Given relatively high capture rates of recyclables, the separate collection shows the largest effect. Among waste fractions, it is the recycling of paper and organic waste treated in anaerobic conditions that reduce the impact the most.

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Anna Zaikova
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LIST OF SYMBOLS

Subscripts

f	fossil

Abbreviations

APC	Air Pollution Control
CED	Cumulative Energy Demand
DOC	Degradable Organic Carbon
EPR	Extended Producer Responsibility
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
MSWI	Municipal Solid Waste Incineration
NIR	Near Infrared
NMVOC	Non-methane Volatile Organic Compounds
PET	Polyethylene Terephthalate
RDF	Refuse Derived Fuel
SC	Sensitivity Coefficient
SNCR	Selective Non-Catalytic Reduction
SRF	Solid Recovered Fuel
TWMS	Territorial Waste Management Scheme
WEEE	Waste Electrical and Electronic Equipment

1 INTRODUCTION

An interference of humankind in the natural environment has become utterly evident as disposed waste, primarily plastic packaging, spreads over oceans and land. With the globalization of social media, the scale of the waste problem is recognized, and awareness of the world community is raising further. Through environmental activism and educational projects related to the topic, the consequences of increasing living standards are introduced to the wide audience in order to engage more people in addressing the issue and act.

While some countries have already shown significant progress in tackling waste management issues, some are only at their starting point towards sustainable waste management. In the USSR, practices of separate collection of glass, paper and other recyclable materials were established and could have become a good basis for the current Russian municipal solid waste (MSW) management system. And yet in the 21st century Russia appeared to be approaching a waste collapse. An absolute majority of MSW in Russia is disposed of in landfills, including numerous unauthorized dumps, and only about 5-7% is recycled (IFC, 2013).

At the same time, increasing rates of waste generation in densely populated cities, particularly in Moscow and Saint Petersburg, as well as poor waste management resulted in a number of protests. Most commonly these were the protests against landfill operations due to the odor nuisance and landfill fires, landfill construction as trans-regional conflicts, and such. Among the most widely known recent conflicts is the one that happened in Shies, located over 1000 km to the north from Moscow. Construction of a new landfill was started there, which is designed for disposal of MSW from Moscow equal to 500 000 tons per year for over 20 years (Ecotehnopark Shies, 2020). Causes of the conflict were the shift of Moscow’s waste burden to the Russian north as well as distrust regarding compliance with environmental standards during landfill construction and operation.

As it was high time for a change, reformation of MSW management system in Russia has started in 2017. According to the national project “Ecology” (The Russian Government, 2018), among other things, the reformation aims to achieve sorting of 60% of the MSW and utilization of 36% of the MSW by 2024. However, means to achieve these goals are questioned by the public and in specific cases rise protests as well.

A challenging situation occurred in the second largest Russian city Saint Petersburg and its surrounding Leningrad region. Statistics show that by 2020 the population of Saint Petersburg reached about 5.4 million permanent residents (Department of the Federal State Statistics Service for St. Petersburg and the Leningrad Region, 2020a), although the number of people living there is estimated to exceed 7 million (IA Krasnaya Vesna, 2020). The local waste management system is no different from the general practice of handling waste in the state, so the absolute majority of MSW is landfilled. Above all, the largest part of MSW generated in Saint Petersburg is transported to the Leningrad region for its disposal, as no other option seems currently possible for a highly populous city being a separate administrative division.

During the reform, plans for a transition to a more sustainable way of managing municipal solid waste were developed in the Leningrad region and Saint Petersburg. However, a large amount of criticism was given to these plans from various parties. Therefore, the development of the MSW handling system in the area may still require consideration, while a basis of it was formed.

Generally, state of the art of waste management system in Russia can be identified to some extent by perspectives of scientific articles published in this field. In the past years, apart from technology, legislative and institutional issues were widely studied, e.g. by Ermolaeva (2018), Tagaeva and Gilmundinov (2020), and by Malyshkov et al. (2019). Furthermore, behavioral patterns of the population regarding the separate collection of waste and possible source separation effectiveness have been examined, e.g. by Solovyeva et al. (2019) and Shabanova (2019). A recent study on environmental activism and its role in administrative decision-making in Russia (Kaminskaya et al., 2019) is another example that points to the need and readiness of the system to be improved.

At the same time, analysis of the system and its development from an environmental perspective has been mostly neglected. Earlier, mathematical modeling of the MSW management system in Saint Petersburg and the Leningrad region was used by Shmelev (2003) to find optimal and less impactful solutions from environmental and economical perspectives. In this work, the overall impact from the system was represented by equivalents of CO_2 emissions, obtained using ratios of relative environmental and economic hazards for other emissions. Recommendations for the system reformation were formed as a result. Then the environmental performance of the system in Saint Petersburg, alongside economical and energy perspectives, was studied by Rodionov and Nakata (2011) through mathematical modeling as well. In this paper, only CO_2 emissions were considered to analyze environmental performance. Both studies use the life cycle thinking in environmental evaluation.

However, no life cycle assessment (LCA) is known to be conducted for Saint Petersburg and the Leningrad region. Given a poor use of life cycle assessment methodology in Russia in general, LCA studies on waste management systems are rather limited. Two cases were published: for Irkutsk city (Starostina et al., 2018, 2014) and Khanty-Mansiysk and Surgut (Kaazke et al., 2013).

Such study for Saint Petersburg and the Leningrad region would form a detailed knowledge on the system's environmental impact and identify possibilities to improve it based on the current situation. Thus, to support the process of building a more sustainable MSW management system and decision-making, this thesis aims at an environmental evaluation of both the current municipal waste management system in the Leningrad region and Saint Petersburg, and its possible developments based on European practices. Subsequently, the first objective consists of a thorough investigation of the current way of MSW management in the area, including existing infrastructure and waste flows. Then possible improvements in the system according to European experience are introduced in the scenarios of the system's development. Mainly, the paper focuses on a comparison of the actual situation and possible developments through LCA. The environmental performance of the system will be assessed with regard to climate change, eutrophication, acidification potentials, and abiotic depletion potential. Through LCA, this thesis also aims to identify the most effective practices for MSW management in the area, as well as waste fractions, treatment of which should be a priority to decrease the environmental impact of the system.

2 CURRENT MUNICIPAL WASTE MANAGEMENT IN THE AREA

2.1 Terminology used in MSW management in Russia

According to the Russian law (Federal Law of 24.06.1998 N 89-FZ, 2020) and similarly to the EU law (EU, 1999), MSW is understood as waste generated by individuals in living areas due to consumption as well as waste with similar composition generated by corporate bodies and independent entrepreneurs. For accounting purposes, waste is classified in the Russian Federation according to its origin and composition, so there are codes that correspond to MSW in the Federal classification catalog of waste (2019). Above that, the hazard of waste is classified with five classes. The fourth and fifth classes, being a low hazard and practically non-hazard classes respectively, contain municipal solid waste apart from other waste.

MSW management as a part of waste management includes activities on waste collection, transportation, processing, utilization, stabilization, and disposal. The terms of collection and transportation of MSW in Russian legislation correspond to common understanding of these terms. Some differences in terminology can arise for other terms. To give an accurate understanding of what these activities imply, the terms are explained further from both theoretical and practical perspectives.

Waste processing is defined as the preliminary treatment of waste through sorting, disassembly, and cleaning (Federal Law of 24.06.1998 N 89-FZ, 2020). Part of waste that is separated during processing can be utilized afterwards.

The *utilization*, in turn, is defined as usage of waste to produce goods or provide services, including cases when waste is reused. Reuse of waste can be done in three ways: when waste is used either for its intended purpose, or after refurbishment, or to obtain components that can be reused. The utilization of waste also includes the use of MSW for energy recovery after useful fractions are recovered in waste processing (Federal Law of 24.06.1998 N 89-FZ, 2020). In practice of current statistical recording, waste utilization indicates separation of saleable material as a result of sorting and does not specifically prove further recycling. Recyclable materials, which have been sorted from the source separated or mixed MSW, can already be referred as a saleable product, given the compliance with the standards on waste subject to recycling. In the same way, separation of screening reject for composting and refuse-derived fuel can be accounted as utilization of waste, even though the waste is not yet utilized.

Waste stabilization is defined as the reduction of waste mass, change of its composition, physical and chemical properties through incineration without energy recovery, or sanitization (Federal Law of 24.06.1998 N 89-FZ, 2020). In practice, thermal treatment, aerobic treatment of waste and treatment of hazardous household waste, when the hazard is reduced, can be referred as waste stabilization.

According to its definition, *waste disposal* includes both landfilling and storage of waste in specialized facilities before utilization, stabilization, or landfilling if it needs to be stored for more than 11 months (Federal Law of 24.06.1998 N 89-FZ, 2020).

2.2 Regulations in the MSW sector

The main document regulating the waste management sector in Russia is the Federal law N89 (FZ-89) "On production and consumption waste" (Federal Law of 24.06.1998 N 89-FZ, 2020), first adopted on June 24, 1998. It underwent several revisions with the latest made in 2020. The amendments to the law have been developed to create such economic conditions that will allow to consider waste as useful materials and return them to the production cycle. Besides, the amendments aimed to attract investments and regulate the legislation so that activities in the field become clearer.

Waste management in Russia is governed by The Ministry of Natural Resources and the Environment, which is a state executive agency responsible for the development of state policy and legal regulation regarding the environment and natural resources, and waste. A subordinate of The Ministry and a controlling body in Russian waste management is the Federal Service for Supervision of Natural Resources (Rosprirodnadzor) with its local representative in each region. Rosprirodnadzor licenses activities in waste management, maintains the waste inventory and the state register of waste disposal facilities, as well as performs other controlling activities (Rosprirodnadzor, 2020).

Local agencies involved in MSW management in the studied region are the Waste Management Committee of the Leningrad Region and the Committee for the improvement of Saint Petersburg. The Waste Management Committee of the Leningrad Region is responsible for the development and implementation of regional state programs in the field of waste management, participation in the implementation of state policy in the Leningrad region and the creation of an integrated waste management system, including waste collection and processing generally (The Waste Management Committee of the Leningrad Region, 2020). The Committee for the improvement of Saint Petersburg, among other duties, ensures the implementation of state policy and carries out state management in the waste management sector in the city (Government of Saint Petersburg, 2020a). As a part of local governments, these Committees develop and execute Regionals programs in waste management. The programs, in turn, establish performance targets to comply with governmental strategy on waste management and activities needed to meet the targets.

Since January 2019, a new system for handling municipal solid waste is under development in Russia. The improved system aims to reduce the amount of landfilled waste, increase secondary use of materials, and make the system transparent and monitorable.

In the new system, activities in MSW handling in each federal subject were centralized and assigned to one or several regional operators. In case there are several regional operators in a federal subject of Russia, each of them is assigned to a certain part of its territory. As an organization, regional operator is responsible for the entire cycle of MSW management at the assigned territory, including collection, transportation, processing, utilization, stabilization and disposal of MSW, and is obliged to make a contract with each MSW generator, either an individual or an organization. The duties may be followed using own facilities or by making contracts with other companies. The regional operator is established on a competitive basis for a period of at least 10 years. In fact, it is an organization that has received a government order and executes instructions from the government, and a private company at the same time.

According to the FZ-89 (Federal Law of 24.06.1998 N 89-FZ, 2020), regional operators work in accordance with a Territorial Waste Management Scheme (TWMS). The TWMS is created for each federal subject of Russia to collect the information on waste flows and waste handling facilities in operation. The TWMSs include data on both MSW and industrial waste.

Practically, the TWMS are meant to serve as a tool for regional operators to organize the waste management system in regions. It is supplemented by an electronic version that contains the same data but enables updating of the databases, data processing, analysis, as well as visualization. The latest TWMSs have been published in July 2019 for the Leningrad region (Waste Management Committee of the Leningrad Region, 2019a) and in July 2020 for Saint Petersburg (Committee for the improvement of Saint Petersburg, 2020).

To help with the waste management sector development in the country, a public company “Russian Environmental Operator” (PPK REO) was established in 2019. A new agency is intended to launch the improved waste management system, to form waste market so that it works naturally without excess investment from the government. This includes methodological work on creation of federal waste management scheme, establishment of waste fees, tariffs and norms, as well as coordination between participants of the market (regions, institutions, waste generators, etc.). Besides, PPK REO controls all regional operators.

Extended producer responsibility (EPR) was introduced in Russia in 2014. It is applied to both producers and importers of goods and packaging. Three paths were available for them to comply with the EPR: to utilize products and packaging at their end-of-life using own facilities, to make a contract with another company for utilization of waste or to pay an environmental fee. According to the changes brought to the FZ-89 in 2020, the second option of compliance with EPR were extended so that the burden of waste utilization can be delegated to PPK REO or an association of producers and importers that provides EPR compliance by organized waste utilization. The manufacturer is also obliged to report to Rosprirodnadzor on the implementation of the utilization rates or on the payment of the environmental fee. Environmental charges payed are then distributed by PPK REO as an investment (Gran Garo, 2020). Regarding existing EPR in Russia, one should consider that the mechanism is still under development.

Actors of a new waste management system and relations between them are depicted in Figure 1. This scheme describes the system in each federal subject of Russia, so that it is applied for Saint Petersburg and the Leningrad region separately.

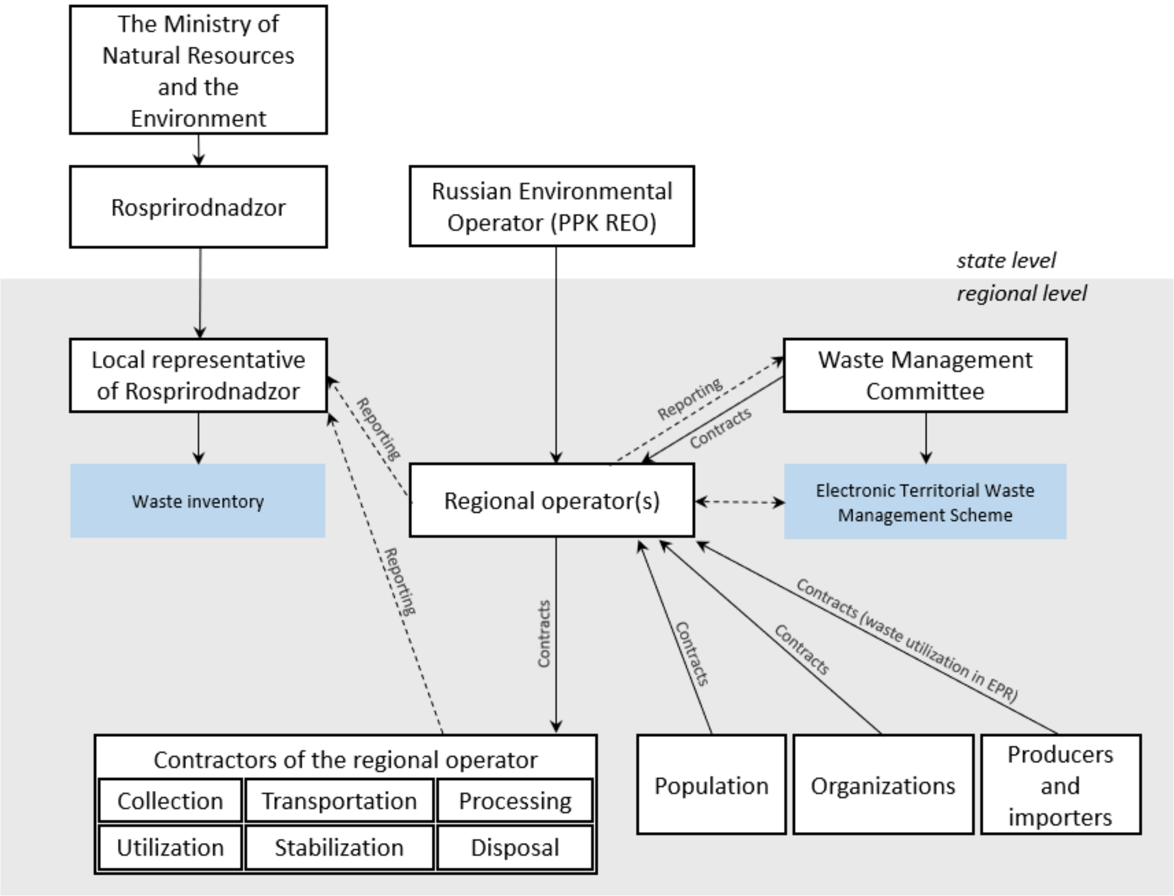

Figure 1. Actors in MSW management in a federal subject of Russia and their relations

Financing of the system under development and new infrastructure, in particular, is organized with three sources: waste fee paid by MSW generators, government subsidies, and environmental fees paid by producers and importers as part of the extended producer responsibility. During the reformation of the waste management system, waste fees were included in payments for public utility services alongside with electricity, heat, and water fees.

2.3 Municipal solid waste generation

Statistical data on waste generation is reported officially by several agencies in Russia, primarily, Federal Department of State statistics and Federal Service for Supervision of Natural Resources. The latter reports systematically regarding the total amount of waste but not municipal solid waste specifically. Thus, the data provided by the Federal Department of State statistics and other reporting institutions in the studied regions are given in Table 1 and Table 2.

Table 1. MSW generation in Saint Petersburg

Year	MSW generation/year		Reference
	t[a]	t/capita[b]	
2019	2 260 201	0.42	Saint Petersburg Environmental Report 2019 (Government of Saint Petersburg, 2020b)
2019	189 384	0.04	Information on the generation, processing, utilization of waste (Federal Service for Supervision in Environmental Management, 2020)
2018	2 235 264	0.42	Saint Petersburg Environmental Report 2018 (Government of Saint Petersburg, 2019a)
2017	1 997 122	0.38	Report on the implementation of the Environmental Policy of St. Petersburg for the period up to 2030 in 2013-2017 (Committee for Natural Resources Environmental Protection and Environmental Safety, 2018)
2016	2 023 039	0.39	
no reference	1 675 056	0.31[c]	TWMS (Committee for the improvement of Saint Petersburg, 2020)

a Calculated based on the data from the referenced source and the assumption for MSW specific weight being equal 231.8 kg/m^3

b Calculated based on official population data for each year (Department of the Federal State Statistics Service for St. Petersburg and the Leningrad Region, 2020b)

c Calculated based on population data in 2018

The data were also represented on a per capita basis to enable its comparability over time and regions. As a side note, the population of Saint Petersburg accounted were in the range of 5.2-5.4 million people in 2016-2019, while the population of the Leningrad region amounted in 1.8-1.9 million people in the same period (Department of the Federal State Statistics Service for St. Petersburg and the Leningrad Region, 2020b).

Table 2. MSW generation in the Leningrad region

Year	MSW generation/year		Reference
	t	t/capita[b]	
2019	805 090	0.44	Database of indicators of municipalities (Federal Department of State statistics, 2020)
2019	1 734 052	0.94	Information on the generation, processing, utilization of waste (Federal Service for Supervision in Environmental Management, 2020)
2018	840 710	0.46	Database of indicators of municipalities (Federal Department of State statistics, 2020)
2017	737 530	0.41	
2016	798 346	0.45	
2016	692 000[a]	0.39	TWMS, electronic version (Waste Management Committee of the Leningrad Region, 2019b)
no reference	711 450	0.39[c]	TWMS (Waste Management Committee of the Leningrad Region, 2019a)

a Calculated based on the data from the referenced source and the assumption for MSW specific weight being equal 231.8 kg/m^3
b Calculated based on official population data for each year (Department of the Federal State Statistics Service for St. Petersburg and the Leningrad Region, 2020b)
c Calculated based on population data in 2018

Most notably, the data provided by Federal Service for Supervision in Environmental Management (**Table 1**) significantly differ from other values and is therefore omitted. Values of MSW generation which originate from the TWMSs cannot be used also as no reference to the time period was provided. The rest of the data is consistent over time.

As can be seen from the tables, waste generation rate fluctuated between 0.38-0.42 tons/capita in Saint Petersburg and between 0.39-0.46 tons/capita in the LR in the recent years. Overall, this highly corresponds to middle-to-high income countries (IFC, 2013). However, the question arises regarding lower MSW generation rates in Saint Petersburg comparing to the LR, which may be partly caused by migration of inhabitants from the city to the countryside on weekends and in summertime. More substantial reason for this is the actual population of the two regions: in 2019 it was estimated to reach 7.1 and 3.2 million people in the city and the region, respectively (IA Krasnaya Vesna, 2020). Calculation of MSW generation rate based on these numbers inverses the result so that in 2019 waste generation rate equals 0.32 t/capita in Saint Petersburg and 0.25 t/capita in the Leningrad region. This also shows generally lower results that correspond to middle-income countries (IFC, 2013).

Taking the bottom-up approach, measurement of MSW generation rate is held regularly by authorities. For apartment buildings, MSW generation rate was measured to be 0.381 tons per resident in Saint Petersburg (Administration of St. Petersburg, 2017) and 0.329 tons per resident in the Leningrad region (Management of the Leningrad Region for the organization and control of waste management activities, 2017). These values support the calculated result for Saint Petersburg but show that those for the Leningrad region may be overestimated.

2.4 Municipal solid waste composition

As systemic studies of waste composition have not been conducted, available statistical information is highly limited. The latest official data on MSW composition in Saint Petersburg is available from 2012. These values and other most credible data are given in Table 3.

Worth mentioning is the fact that MSW composition has certainly changed since 2012. In particular, the use of delivery services has grown significantly, and therefore consumption of packaging materials increased accordingly. In larger cities, especially in Saint Petersburg, food delivery is a considerable market sector these days, resulting in an increase of plastic, paper, and cardboard shares in waste composition.

Table 3. Composition of MSW in Saint Petersburg

Waste fraction	(Committee for the improvement of Saint Petersburg, 2012)[a]	(Rodionov and Nakata, 2011)[b] 2002	(St. Petersburg Scientific Center of the Russian Academy of Sciences, 2011)[c]
Food waste, %	27.4	34.9	25-30
Paper and cardboard, %	21.5	15.6	15-20
Non-ferrous metals, %	0.8	4.6	1
Ferrous metals, %	3.8		4-5
Glass, %	8.9	13.7	10-15
Plastics, %	15.2	11.3	10-14
PET, %	3.4		
HDPE, %	1		
PP, %	0.8		
PE films, %	7.4		
PVC, %	0.1		
Other plastics, %	2.5		
Leather, rubber, %	4.3	1.0	1-2
Textile, %		3.8	3-5
Wood, %	2.5	0.8	4
Inert materials, %	12.8	-	4-5
Other materials, %	2.8	14.3	1-2
Composite waste, %	-	-	>5
Garden and park waste, %	-	-	2-4
Screening reject <16 mm, %	-	-	8-10

a Data collection method is not known
b Data from 2002, the data collection method is not known
c Data obtained at MSW processing plants (MPBO plants in Yanino and Volkhonskoye) in the early 2000s, averaged and corrected according to the trends in EU

In the Leningrad region, the content of MSW has never been systematically studied (Nikanorova et al., 2019). Traditionally, it is considered to be similar to the composition of waste in St. Petersburg. A retrospective analysis of this issue was done by Nikanorova et al.

(2019). However, AO "DAR/VODGEO" (2010) refers to a study focused on MSW composition in the Leningrad region and conducted by the Laboratory for monitoring and cadastre of waste NPO "Center for Improvement and Waste Management". The results of the study are presented in Table 4.

Table 4. Composition of MSW in the Leningrad region

Waste fraction	(AO “DAR/VODGEO,” 2010)[a]	(AO “DAR/VODGEO,” 2010)[b]
Food waste, %	15.0	28.04
Paper and cardboard, %	8.0	20.21
Non-ferrous metals, %	0.7	1
Ferrous metals, %	8.0	3.28
Glass, %	16.0	11.74
Plastics, %	10.0	6.43
Leather, rubber, %	8.0	2.31
Textile, %	2.0	7.23
Wood, %	0.5	3.47
Bones, %	3.5	1.58
Garden and park waste, %	0.5	-
Screening reject <15 mm, %	10.0	4.73
Other materials, %	14.3	8.39
Inert materials, %	1.5	1.58

a Data from 2010, obtained during in-situ measurements
b The same, but a weighted average considering the population and composition of MSW from Kirovsky, Lomonosovsky and Tosnensky districts of the LR

There may also be considerable seasonal changes in composition and generation in both Saint Petersburg and the Leningrad region. In autumn MSW generation is at its maximum in both regions due to the increasing amount of garden and park waste. In Saint Petersburg, the least amount of generated MSW is observed in early summer as its residents move to the countryside (Denafas et al., 2014).

2.5 Existing MSW management system

MSW management system in both Saint Petersburg and Leningrad region is largely based on landfilling of mixed MSW. Part of mixed waste undergoes processing, i.e. separating of materials which can be further recycled, composted or otherwise utilized.

Data on handling of MSW in Saint Petersburg and the Leningrad region is given in Table 5 and Table 6, respectively. To track the changes in the system's state, data from the years 2016-2019 was reviewed. The data from the latest approved TWMSs is presented as well. For the Leningrad region, data from an electronic model of TWMS is available as well.

Table 5. MSW handling in Saint Petersburg

Year	no reference	2016	2017	2018	2019
Reference	(Committee for the improvement of Saint Petersburg, 2020)	(Committee for Natural Resources Environmental Protection and Environmental Safety, 2018) [a]		(Government of Saint Petersburg, 2019a) [a]	(Government of Saint Petersburg, 2020b) [a]
Generation, t_{MSW}/a	1 675 056	2 023 040	1 997 122	2 235 260	2 260 201
Processing, t_{MSW}/a (%)	57 271 (3%)	352 450 (17%)	347 095 (17%)	466 687 (21%)	610 254 (27%)
Stabilization, t_{MSW}/a (%)	176 672 (11%)				
Utilization, t_{MSW}/a (%)	83 168 (5%)	no data	no data	no data	
Landfilling[b], t_{MSW}/a (%)	1 357 946 (81%)	1 670 589 (83%)	1 650 027 (83%)	1 768 809 (79%)	1 649 946 (73%)

a Calculated based on the data from the referenced source and the assumption for MSW specific weight being equal 231.8 kg/m^3

b Values do not include refuse waste from waste processing that is further landfilled

Table 6. MSW handling in the Leningrad region

Year	no reference	2016	2016 [a]	2017	2018	2019
Reference	Information on future plan in TWMS (Waste Management Committee of the Leningrad Region, 2019a)	(Waste Management Committee of the Leningrad Region, 2019b)	(Federal Department of State statistics, 2020)			
Generation, t_{MSW}/a	711 450	692 000	798 346	737 530	840 710	805 090
Processing, t_{MSW}/a (%)	499 180 (70%)	100 000 (14%)	13 862 (2%)	48 900 (7%)	85 300 (10%)	96 360 (12%)
Stabilization,t_{MSW}/a (%)	261 (0%)	180 000 (26%)	no data	no data	no data	no data
Utilization, t_{MSW}/a (%)	49 920 (7%)	0 (0%)	no data	no data	no data	no data
Landfilling, t_{MSW}/a (%)	661 540 (93%)	504 000 (73%)	no data	no data	no data	no data
a Calculated based on the data from the referenced source (specific weight equals 231.8 kg/m^3)						

A remark should be made for the values from Table 6 provided by the TWMS (Waste Management Committee of the Leningrad Region, 2019a). The amount of processed MSW differs greatly comparing to values from other sources. As the reference year is not provided for these data, it can be interpreted as a value planned for the future time period.

2.5.1 MSW collection

In apartment buildings of both studied regions, accumulation of waste is most commonly handled at waste collection points using 6 m^3 containers or 750 l bins. When filled, containers are meant to be used for the transportation of waste to the treatment facilities, while bins are emptied at the site. Some buildings are equipped with garbage chute systems.

A system of non-replaceable containers is also used to collect MSW from the population living in the individual housing.

In both Saint Petersburg and Leningrad region, source separation is not employed as a common practice. The Leningrad region TWMS suggests that only a tiny portion of waste collection points are equipped with separate bins for recyclables (Waste Management Committee of the Leningrad Region, 2019a). However, some containers for separate collection of waste, e.g. privately installed, could be overlooked in the official data.

Separate collection of some waste fractions is currently implemented by organizations in limited territories. Activists, most notably represented by RazDelniy Sbor, hold regular or single-time actions to collect the recyclables. As an example, in 2019 RazDelniy Sbor reported on collection of 310 tons of various recyclable materials in Saint Petersburg, including paper and cardboard, glass, metals, different types of plastics, and Tetra Pak packaging (RazDelniy Sbor, 2020a).

In Saint Petersburg there are currently 14 organizations which provide containers, collect and stock recyclables to sell them to recyclers; some of them operate in the Leningrad region as well (RazDelniy Sbor, 2020b). These companies tend to focus on specific secondary materials, e.g. OOO “Rekast” collects PET bottles and HDPE containers, OOO “YUVI SPb” collects PET bottles, paper, and cardboard, “Steklovozik” collects glass only. Assessment of the amount of separately collected recyclables is challenging at the moment.

Separate collection of hazardous household waste is not fully developed in the studied area. In Saint Petersburg, hazardous waste such as mercury-containing lamps, thermometers, small-sized batteries can be collected separately in special boxes installed around the city in 2018, although the rate of separate collection can be low due to insufficient engagement of residents. Larger items of hazardous waste, including waste electrical and electronic equipment (WEEE) can be collected by the mobile collection points. WEEE can also be collected at some electronic shops. In the Leningrad region, similar system of mobile collection points operated for hazardous waste collection, however its operation was interrupted by the reformation of waste management system.

2.5.2 MSW transportation

Transportation of MSW in the studied region is handled by a number of private companies. In Saint Petersburg, the majority of the market is occupied by AO “Autopark No.1 “Spetstrans” and AO “Autopark No.6 “Spetstrans”. As the reformation of the system proceeds, these companies are expected to work as subcontractors of regional operators.

When transporting MSW, transport companies often use a two-stage technology, i.e. utilizing transfer stations to cut the transportation costs. At the transfer stations, waste is reloaded into larger containers: mainly from 6 m^3 containers to 27 m^3. The main purpose here is to shred bulky waste and compact the waste into large capacity containers for heavy-duty garbage trucks. In 2010, there were five transfer stations officially registered in Saint Petersburg as well as some temporary, not fully authorized transfer stations (St. Petersburg Scientific Center of the Russian Academy of Sciences, 2011). Operation of several other transfer stations can be recognized nowadays. Likewise, transfer stations are used in the Leningrad region, particularly, several stations owned by OOO “Lel’-EKO” in Kirishi.

2.5.3 Mechanical and biological treatment of MSW

As shown earlier, roughly 20% of MSW in Saint Petersburg and around 10% of MSW in the Leningrad region were sent to processing in recent years. The treatment options currently applied for this waste are sorting of mixed waste with the following recycling of recovered useful fractions, composting of recovered organics, and in some cases production of refuse derived fuel (RDF) from the residues of sorting process. Small amount of mixed MSW or specific fractions is known to be treated thermally in incineration or pyrolysis processes (Waste Management Committee of the Leningrad Region, 2019a). If hazardous waste is separated from MSW, it is stabilized accordingly.

Facilities which handle MSW usually include several waste treatment operations, e.g. some landfills are supplemented with sorting stations and composting plants. Sorting stations can be also a separate facility located far from a landfill, where composting is optional.

Sorting of mixed MSW is mostly done manually and, in some cases, mechanically. Depending on recovered materials, three types of sorting lines are commonly used: manual sorting of recyclable materials with mechanical sorting of ferrous metals, the same but supplemented with mechanical screening to separate organics, and, finally, automated sorting lines, which still can be supplemented by manual sorting if needed. Besides, some sorting can be implemented at transfer stations, which is most probably done manually.

When it comes to manual sorting, generally its efficiency is as low as 7% of incoming MSW (Il’inykh G.V., 2014). The value can reach 12% when more fractions are separated from the mixed flow (RazDel’nyy Sbor online interview, 2020). Higher sorting efficiencies correspond to cases with separation of organic fraction for further composting.

Composting is applied to organic waste that is separated from mixed waste through mechanical screening as it is not suitable for further sorting. This screening reject contains food waste, foliage, and other organics alongside with non-organic material that is small enough to be screened out, e.g. glass cullet. Garden waste can be used in composting in some cases if collected separately. Composting methods commonly include container and drum composting with the following maturation in windrows; self-sufficient windrow composting is possible.

The largest and most interesting facilities, which process MSW in the two regions, will be described in detail further. The choice of such companies is mostly based on the data from the TWMSs of the two regions.

2.5.3.1 MPBO-2

Perhaps the most important plant in the waste management system in Saint Petersburg is the “Plant for mechanical processing of household waste” (“Zavod po Mehanizirovannoy Pererabotke Bitovih Othodov”, MPBO). It was created back in the USSR, primarily to process organic waste into compost and meet the needs of agriculture and urban landscaping. The operation of the plant started in 1970. Since then, the main purpose of the facility was to produce compost through drum composting. However, now, when there is no separate collection of organic waste, the plant has to reorient its operation to the current composition of MSW. (RazDelniy Sbor, 2015)

The MPBO plant has two operational facilities: the main one located just beyond the administrative border of Saint Petersburg, Yanino-1 (MPBO-2), and its branch, Pilot plant MPBO, located in Saint Petersburg, Volkhonskoe highway, 116. The joint capacity of the two plants was planned to be up to 500 000 tons of MSW annually at its full production scale (MPBO-2, 2018a).

The MPBO plant operates as a mechanical biological treatment plant. Each facility has a sorting line for recyclable materials extraction and separation of organic fraction for composting. The aerobic processing of waste is operated by ten drums KM102A depicted in Figure 2, each has a volume of 750 m^3 (Committee for the improvement of Saint Petersburg, 2020). The waste is treated for 48 hours at 60°C in drums (MPBO-2, 2018a); the waste undergoes further curing outside.

Figure 2. The drum for composting of organic waste at MPBO-2 (MPBO-2, 2018a)

A composting process in rotating drums features in a faster decomposition of biomass due to its constant aeration; the retention time is reduced to 1-10 days (Boldrin et al., 2009). The microflora needed for the aerobic process is available in the required quantities in the MSW.

The activation of its activity is ensured by mixing the waste during the rotation of the drums and aeration of the compostable mass.

At the initial stage of the sorting process, bulky items are removed from the waste, such as tires, furniture, mattresses. Bags opening is done manually, after this the waste is fed to two conveyor lines, where 10 fractions are removed: cardboard, PET plastics, HDPE, LDPE, metal, textiles, etc. The sorting process is carried out manually, while ferrous metals are extracted by a magnetic separator. The data which were obtained during an excursion to this facility organized by eco-activists states that this way it is possible to separate only 3-5% of recyclable materials in total. (RazDelniy Sbor, 2015) According to the data obtained from the representative of the Ecology Department at MPBO-2, recyclables recovery rate for manual separation accounts for only 2-3% of input MSW (MPBO-2 phone interview, 2020).

After the manual separation of recyclables, the remaining waste is screened in a rotary trommel to extract waste less than 250 mm in size for drum composting. The resulting screening reject subject to composting is shown in Figure 3. It may contain hazardous waste, such as electronic devices, batteries, and those containing mercury. Therefore, the produced compost is contaminated with heavy metals and is not allowed by sanitary services to be used in agriculture (Committee for the improvement of Saint Petersburg, 2012). According to data from MPBO, 19% of resulted product is separated and used for landscaping, 75% is used as a daily landfill cover material (MPBO-2 phone interview, 2020). The rest 6% are considered mass loses.

Figure 3. Screening reject that is composted in rotary drums at MPBO-2 (RazDelniy Sbor, 2015)

2.5.3.2 Staroobryadcheskaya sorting station

Two MSW treatment plants “Staroobryadcheskaya” and “Predportovaya” are owned by OOO “Resursosbereshenie”. According to the project documentation, plants have identical sorting processes and capacities equal to 100 000 tons of MSW annually at each plant (OOO “KOSMOS,” 2016). The plants feature in automated sorting lines, which include optical sorting. Mixed municipal waste is processed there to recover recyclable fractions, including organic waste for further stabilization through composting. Refuse-derived fuel (RDF) is produced from the remaining part of the waste flow. The remaining part of waste in the sorting process is sent to the Novyy Svet landfill, which is owned by OOO “Resursosbereshenie” as well (OOO “KOSMOS,” 2016).

Before the actual sorting, bulky waste is sorted out. Then the waste flow is sent to the primary shredder, which opens the bags and reduces the size of waste to be suitable for further separation processes. At this step of the processing, ferrous metal waste is sorted out by a magnetic separator, as depicted in Figure 4. Separated ferrous metal is then sent to recycling. (OOO “KOSMOS,” 2016)

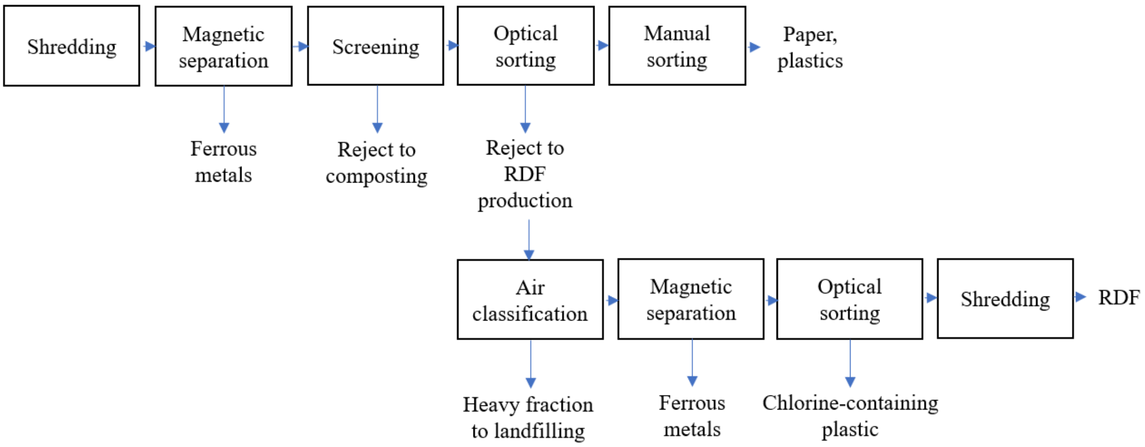

Figure 4. A scheme of the sorting line at Staroobryadcheskaya plant

At the next step of the processing, a disc screen separates a fine fraction of waste up to 80 mm in size to separate organic fraction and to increase efficiency of further sorting. The efficiency of the screening can reach 85-90% (OOO “KOSMOS,” 2016). The screening reject contains food waste, foliage, and other wet organics, as well as sand, stones, street sweepings, and some paper. ´However, according to the excursion materials from the facility (RazDelniy Sbor, 2020c), in fact, the mixture comprises a significant part of plastics, glass, paper, and possibly hazardous waste, e.g. batteries. After separation, undersize flow is subject to windrow composting at the landfill site as depicted in Figure 5. This screening reject is not considered as waste but a salable product and is standardized. Composting of such a product result in production of a material not acceptable for agricultural use, so it is primarily used as a landfill cover at the Novyy Svet landfill.

Figure 5. Windrow composting of MSW undersize fraction, Novyy Svet landfill (Malyukhin et al., 2018)

Further, larger fractions pass through several optical separators, sorting out plastics and paper (Figure 6). Manual sorting is involved in the process for sorting of different plastic fractions from a plastic waste flow after optical separation. Glass items are inevitably broken in a disc screen, thus cannot be separated for further treatment. Recyclable fractions such as paper, ferrous metals, and plastics are pressed and baled before sending for recycling.

Figure 6. Paper fraction, which was sorted out by an optical separator, Staroobryadcheskaya waste processing plant (RazDelniy Sbor, 2020c)

After that, an air classifier separates waste flow into light and heavy fractions, where light fraction is used further for RDF production. An optical separation of waste containing chlorine is included for this purpose (Bushikhin et al., 2015). Additional metal separation is used as well. Paper and cardboard, textile, wood and other fractions that cannot be sorted or are not suitable for processing are crushed in a shredder and converted into RDF. RDF obtained at these stations was standardized and called “Topal-1”. It is said to be produced for utilization at a cement kiln owned by OAO "Slantsi Cement Plant "CESLA"(Bushikhin et al., 2015).

2.5.3.3 Lel’-EKO waste processing plant

OOO “Lel'-EKO” owns a waste processing plant and a landfill next to the Kirishi town in the Leningrad region. Composting facility for organic waste, sewage sludge, wood and plant residues is located next to the landfill site as well. The company reported on 22585 tons of

MSW recovered for further utilization in 2018 (Waste Management Committee of the Leningrad Region, 2019a).

MSW sorting is carried out using a mobile sorting line A-NO-02, which is a sorting booth mounted on a chassis for rapid deployment. Waste coming to the sorting station is sorted on a conveyor with the separation of the following fractions: paper and cardboard, plastics, glass, scrap of ferrous and non-ferrous metals, textiles, leather, wood, rubber waste including tires, biodegradable waste. In addition, hazardous waste is separated. Separated useful fractions are subject to subsequent utilization. The overall efficiency of the processes of separation of secondary fractions is stated to reach 25-37% of the initial volume of waste entering the plant. Sorting residues are landfilled. (Federal Service for Supervision of Consumer Rights Protection and Human Welfare, 2020)

Composting is carried out in an automated container BioEcoModul AF. The unit is equipped with an air purification module. Composting results in the 60% loss of the initial mass of the waste. Windrow composting is also used for treatment of organics. (Federal Service for Supervision of Consumer Rights Protection and Human Welfare, 2020)

2.5.3.4 OOO “TEK” – sorting and pyrolysis plants

According to the Federal Service for Supervision of Consumer Rights Protection and Human Welfare (2020), OOO “TEK” operates a sorting station in Saint Petersburg and a pyrolysis plant for utilization of MSW in the Leningrad region.

Sorting is operated to separate metals, paper and cardboard, as well as combustible fraction for pyrolysis. The loading of waste onto the feeding conveyor belt is carried out using a loader. At the same time, bulky waste is preliminarily removed for crushing. Crushed bulky waste and sorted combustible waste are loaded into a container and transported to be utilized in the low-temperature pyrolysis process in the Leningrad region. The remaining waste from the sorting belt conveyor is loaded into a container and transported to ZAO Promotkhody landfill in the Leningrad region.

Pyrolysis plant is equipped with two pyrolysis units, which are used to utilize combustible MSW alongside with waste tires and oil sludge. The company reported on utilization of 6315 tons/a of MSW in the LR, and 2436 tons/a sent to utilization in Saint Petersburg (Committee for the improvement of Saint Petersburg, 2020; Waste Management Committee of the Leningrad Region, 2019a). In the process of pyrolysis, a char, pyrolysis liquid, metal residue, and pyrolysis gas are formed. According to the sanitary documentation of the plant (Federal Service for Supervision of Consumer Rights Protection and Human Welfare, 2020), pyrolysis gases are sent back to the furnace to support incineration process. The pyrolysis liquid is used to start the pyrolysis process. Metal residue is sent for metal recycling, while char is disposed of in a landfill.

Figure 7. Pyrolysis unit (left) and sorting station (right) operated by OOO "TEK" (TEK, 2019)

Apart from the abovementioned processing of MSW, there are several other facilities across the studied regions. According to the TWMS of Saint Petersburg, 5638 tons/a of recyclable materials are recovered at the sorting station “Kolpino” owned by OOO "Sinergiya". There MSW is processed using a sorting line "Megalion" as described further. First, the bags are opened, ferrous metals are recovered by a magnetic separator, recyclable fractions are manually selected. Hazardous waste is sorted out and sent for further stabilization. Besides, WEEE is processed at the facility: appliances undergo disassembly by elements and fractions, then they are packed according to the buyer's specifications and sent to the finished product warehouse. Sorting reject is sent to a landfill.

Several sorting stations are operated next to landfills in the Leningrad region. According to the TWMS, AO “Waste management company in the Leningrad region” runs four of them:

in the Priozerskiy, Volkhovskiy, Slantsevskiy, and Kingiseppskiy districts. The TWMS for the LR states that the amounts of MSW recovered and sent to utilization were as follows in 2018: 5792 tons of MSW at the Kingisepp landfill, 7050 tons at the landfill in Priozerskiy district, 809 tons at the Slantsy landfill, 607 tons at the Volkhov landfill.

Sorting stations listed above employ manual sorting to separate recyclable materials. Particularly, it is applicable to sorting at the Kingisepp landfill, where paper and cardboard, glass, PET bottles, aluminum cans, plastic containers, metals are recovered from the mixed MSW. According to the design documentation, recovery rate equals 15% (OOO «Stroitel'naya Kompaniya «Gidrokor», 2019), though it can be less in practice. Compostable material is screened out at one of these sorting facilities, the one located in the Priozerskiy district (Federal Service for Supervision of Consumer Rights Protection and Human Welfare, 2020).

2.5.4 Material recovery

There are several actors along the material recycling chain. First, there are procurers, which collect and prepare the waste to be sold to recyclers. They collect materials after MSW is sorted at the sorting centers and may carry out cleaning and additional sorting. Then, there are enterprises which perform actual recycling, i.e. conversion of waste to a material ready for use in production. Finally, those who use recycled materials in production may also be a part of material recycling chain.

Generally, recyclers dealing with paper and cardboard, plastics, and wooden parts are currently focused on industrial waste and waste from commerce sources (chain markets and such). They may have 50-80% and in some cases 100 % of feedstock with non-MWS origin (Gran Garo, 2020). This happens due to high contamination of material from municipal solid waste, which is, in turn, caused by a single-bin collection system or poor separate collection quality, and leads to higher manufacturing costs.

Even though the share of PET bottles is relatively low in the composition of plastics in MSW, it is the ease of extraction of PET containers that leads to high share of PET in the total plastic waste, separated in processing plants. As a result, PET accounts for around half of the total Russian plastics separated for recycling (RUPEC, 2017). Furthermore, based on a list of procurers and recyclers created by Razdel’nyy Svor association (RazDelniy Sbor, 2020b), it is also HDPE-containers and PE films that are collected for recycling among plastics.

As an example of plastic recycling company, Ultrix, which is located in the Leningrad region, recycles PET mechanically to obtain PET flex. Sorted materials is crushed, cleaned using water heated to 89 degrees and caustic soda, and separated via flotation. After drying, the PET-flex is obtained, ready for processing into geotextiles, synthetic winterizer, noise and heat insulation, etc. Besides, the partners of "Ultrix" in Krasnoe Selo in the Leningrad region produce polymer sandy paving slabs from the material rejected at the stage of flotation (Ultrix, 2020).

Generally, secondary polymers in Russia are mainly used to produce goods with lower consumer properties. About 80% of recycled PET is used to produce technical fibers, ribbons, and other products for technical use. The rest is used for sheet and film production, while some part of it can serve as an additive to primary PET in the manufacturing of preforms. Recycled polyethylene is used to produce geotextiles, boxes, containers, pipes and non-food films.

Based on the analysis on Russian paper recycling industry from 2010 (Research.Techart, 2010), the most consumed material from paper and cardboard waste fraction is cardboard, which accounts for almost 60% of the total amount of the fraction. Furthermore, more than 18% of the paper and cardboard fraction is newspaper. Majority of the collected waste paper, which constitute 75% from total separated material, is recycled at cardboard and paper mills (Research.Techart, 2010). It is mostly used to produce low quality paper, toilet paper, napkins, cardboard. Partly it can be utilized to produce roofing materials.

Waste glass or cullet is mostly transported for recycling beyond the studied area, e.g. Russian cities Tver’ and Nizhniy Novgorod (Steklovozik, 2020).

2.5.5 Landfilling as a basis of the system

Landfilling is currently applied for the majority of municipal solid waste in the studied regions. Though available sources of information disagree on the exact percentage of MSW disposed of in landfills, the amount of MSW sent directly to landfills varied between 73-93% for Saint Petersburg and 79-83% for the Leningrad region during 2016-2019 (see Table 5 and Table 6). Actual values are substantially higher due to the landfilling of the sorting reject, which is not shown in the reported values.

According to the data from the TWMSs, all the waste from Saint Petersburg subject to landfilling is disposed of in the Leningrad region. Six landfill sites are indicated to serve for this purpose, namely

- Kingisepp landfill operated by AO “Waste Management Company in the Leningrad Region”,
- OOO “Novyy Svet-Eko” landfill,
- OOO “Poligon TBO” landfill near Lepsari,
- ZAO “Promotkhody” landfill,
- OOO “Auto-Berkut” landfill,
- OOO “Profspectrans” landfill (Waste Management Committee of the Leningrad Region, 2019a).

Above those, the LR TWMS gives data on ten more landfills used for the disposal of MSW generated in the LR (Waste Management Committee of the Leningrad Region, 2019a).

The abovementioned landfills are used for the disposal of municipal solid waste, in some cases including construction and demolition waste. The landfill gas (LFG) collection system is not generally used; the same applies to leachate treatment, possibly with a justification of such design solution.

The Novyy Svet landfill can be defined as a sanitary one, i.e. it is equipped with the LFG collection system. The landfill has been operating since 2001. The design capacity of the landfill is 18 million tons with the annual capacity being equal to 900 thousand tons (OOO “KOSMOS,” 2016). With the 20-years planned life of the landfill, it is now approaching its capacity limit.

At the Novyy Svet landfill, landfill gas is used for combustion in gas engines to produce electricity. Gas combustion units are shown in Figure 8. The generated electricity is supplied to the district power grid and used for the facility's own needs. About 50% of the landfill gas mass is methane. No gas storage is applied; therefore, an excess gas is flared. In case of insufficient gas flow, gas engine is out of the operation. (ZAO NG - Energo, 2013)

Figure 8. Landfill gas combustion units at Novyy Svet landfill (Gatchina municipality of Leningrad region, 2018)

The leachate is collected by sand-gravel drainage and then flows to an underground tank. It is then used for moisturizing of the landfilled waste masses as one way to compact it and to prevent landfill fires. The landfill is not considered as a bioreactor as the moisture content of waste is not monitored. As stated in the project documentation, no discharge of water takes place, since water deficiency was found by the calculation of landfill body water balance. (OOO “KOSMOS,” 2016)

Another example is a Kingisepp landfill in the Leningrad region. The landfill gas collection is not applied there. Although there is a passive degassing system – a system of vertical wells installed in a landfill body that helps in prevention of landfill fires. Leachate is not treated there but only collected by the drainage system and transported to a tank. The tank and the landfill body are communicating vessels, so that it is possible to monitor leachate level in the landfill. Further, the leachate is recirculated to enhance decomposition of organic matter in the waste masses. In case excess leachate is formed, it is diluted to meet the water quality standards and then discharged into the environment. (OOO «Stroitel’naya Kompaniya «Gidrokor», 2019)

The environmental impact of landfilled waste is further deteriorated by a poor source separation of hazardous waste in the studied region. Most of it can be expected to end up in MSW landfills even though separation of hazardous waste is implemented at some sorting facilities.

Above that, illegal landfilling of MSW is a common problem in the studied region. According to the recently reported data, 515 unauthorized landfills were known in 2018 in Saint Petersburg, 473 of which were removed during the year. In 2019, presence of 310 dumping places were reported again. (Government of Saint Petersburg, 2020b)

2.6 Reformation of MSW management system underway

Even though the reformation was discussed before that, it was the National Project “Ecology” (Ministry of Natural Resources and the Environment of the Russian Federation, 2018) that established clear step-by-step targets within the reformation of waste sector. At the moment, part of the objectives has been already fulfilled, including establishing a public company to support the reformation, preparation of regulatory support for the reformation, creating an inventory of MSW disposal locations, modernization of the unified state waste accounting system, and developing territorial waste management schemes in each region. To proceed, new facilities for waste processing and utilization should be built.

As one of the main goals of the reformation, rates of MSW processing and utilizations must be increased. Overall targets is Russia, according to the National Project “Ecology” (Ministry of Natural Resources and the Environment of the Russian Federation, 2018), are as follows: share of MSW sent to processing from the total amount of generated MSW should reach 60% and share of MSW sent to utilization should reach 36% by 2024.

2.6.1 Reformation in Leningrad region

AO “Waste management company in the Leningrad region” has been chosen as a regional operator and now should achieve the reform’s objectives. The targets for processing and utilization of MSW amount to 41% and 8% respectively in the Leningrad region (Waste Management Committee of the Leningrad Region, 2019a). Regarding the source separation of MSW, the implementation of organic fraction separate collection is planned according to the TWMS in Leningrad region.

A general target for the future mentioned in the media (Letyukhina, 2019) is to process the whole amount of generated MSW. According to the TWMS (Waste Management Committee of the Leningrad Region, 2019a), several waste processing facilities with the total capacity 2 650 000 tons are planned according to the TWMS, although an uncertain part of this capacity is meant for industrial waste processing. A facility for MSW processing and landfilling in Priozersk, which was mentioned in the TWMS, is already operated.

Construction of two other facilities have been discussed in the region. Firstly, two projects were published by AO “Waste management company in the Leningrad region” for public discussion. One of them is the project of increasing Kingisepp landfill capacity; the other one is the construction of a facility for processing MSW in Kingisepp. Secondly, MSW processing facility in Gatchina was planned in the TWMS and described in more detail by Letyukhina (2019).

2.6.1.1 Gatchina facility

The TWMS for the Leningrad regions states the planned annual capacity of Gatchina facility to be 500 000 tons at the first stage with further development to 1 000 000 tons annual capacity. According to Letyukhina (2019), plant's technological solution involves automated waste sorting with the production of SRF. SRF fuel can be used in solid fuel boilers with fluidized bed boilers to generate thermal and electrical energy. Part of the fuel would cover company's own needs in electricity, while the rest would be supplied to the network. Possible utilization of SRF in cement kilns was mentioned as well. As stated in the article, the enterprise would be able to utilize up to 75% of the incoming MSW. In this volume, 15% is recycling of glass, metal and PET, 26% is organic waste for composting, 34% is material for SRF fuel.

2.6.1.2 Kingisepp facility

The project of Kingisepp facility includes sorting, composting, and landfilling of MSW. The design capacity equals 300 000 tons/a. Recovery rate for recyclables is stated to reach 15%, while 76 000 tons of MSW (25% of incoming waste) is planned to be composted (OOO «Stroitel’naya Kompaniya «Gidrokor», 2020).

Pre-sorting is done to separate bulky waste and glass. The drum screen separates the fraction less than 70 mm in size. An undersized fraction undergoes metals separation and is sent to composting site. To separate recyclable materials such as paper and cardboard, film and containers made of LDPE, HDPE, PP, PET bottles, manual sorting is applied. Non-ferrous metals are planned to be separated as well, though the method of separation is not stated in the design documents. Ferrous metals are sorted out by a magnetic separator.

Composting method implies using concrete boxes (40 m in length, 8 m in width and 1 m in height). Inside these boxes, waste is formed in piles 3,5 m in height. Boxes are covered by a membrane, which allows water and carbon dioxide to permeate through it but is impermeable for odorous organic compounds. After composting of 76 000 tons of screening residue, 45 600 tons of compost at a density of 0.65 t/m^3 is obtained. This amount of compost is stated by the project documentation to completely cover the need for the landfill intermediate cover material.

Landfill project includes a passive degassing system, i.e. installation of degassing wells with no landfill gas collection. Leachate is collected by the drainage system and accumulated in a well, so that it is possible to monitor leachate level in the landfill body, but it is not collected for treatment.

2.6.2 Reformation in Saint Petersburg

As Saint Petersburg is divided into northern and southern zones for waste management, each must have its own waste management operator. At the end of 2018, two contests on establishing a regional operator were held, and both were litigated. In the south, after long legal proceedings, the results were invalidated. In the north, proceedings are still underway, and until then the operator is considered to be MPBO-2, subordinate to the Saint Petersburg

Committee for the Improvement. After that, in summer 2020, the president of Russia has approved the establishment of a common regional operator for both regions.

The Saint Petersburg target for MSW sent to utilization is larger than the one for sorting, amounting to 37.6% and 11.1% respectively (Committee for the improvement of Saint Petersburg, 2020). This can be explained in different ways. First, this could be considered a clerical error, although these exact target values are claimed to be target values in a regional plan for the national project (Government of Saint Petersburg, 2019b) as well. Apart from that, theoretically, such an exceedance of the utilization rate can be reached by increased share of direct incineration of MSW.

In terms of source separation practices, the current TWMS in Saint Petersburg refers to a “Procedure on MSW collection” (Committee for the improvement of St. Petersburg, 2018). It states that source separation in the city is organized by a regional operator and primarily involves separate collection of the organic fraction.

Apart from implementation of two-bin system, separate collection of specific types of household hazardous waste must be done according to the Procedure. This implies collection of mercury-containing waste, batteries and accumulators in separate containers, which already functions in the city. Separate collection of other hazardous waste in MSW, e.g. tires, expired medicines and such, is not considered by the Procedure.

As for development of new infrastructure and increasing rates of sorting and recycling (according to applied terminology, processing and utilization), TWMS of the city relies on an investment program of the MPBO-2 plant (MPBO-2, 2018b). The two facilities, owned by the company, are planned to be developed and the capacity of each to be increased to 900 000 tons of MSW annually. Each of two facilities is expected to recover 360 000 tons of secondary materials during sorting process (considering the mathematics behind this and further statements, these secondary materials include screening reject as well). Furthermore, 300 000 tons are expected to be stabilized; this is most possibly related to aerobic treatment of organic fraction in rotating drums. The remaining waste after sorting, which amounts in 500 000 tons, would be utilized in construction material production. Besides, stabilization of hazardous household waste is stated to cover 120 tons of incoming MSW at each facility. (MPBO-2, 2018b)

This plan has been criticized by various parties, when public discussion of a TWMS project was held by the Committee for the Improvement. The major argument for an inadequacy of the solution was related to operability of logistic activities for these facilities, given the capacity increased.

When considering TWMSs of both Saint Petersburg and the Leningrad region, one can point to a poor correlation of them: Saint Petersburg claimed that 1 800 000 tons of MSW are to be sorted at MPBO-2, while Leningrad region’s capacities for waste processing are significantly higher than those needed for own MSW in the region (roughly 2 650 000 tons are planned to be processed, with the generation of MSW equal to around 840 000 tons in the region). Therefore, there is a clear lack of compatibility of developed TWMSs of two areas, whose MSW management systems so closely related. However, in August 2020, governments of the two regions agreed to introduce a new TWMS which covers both regions by the end of 2020.

At the same time, according to Federal Law No. 483-FZ of 25.12.2018, Saint Petersburg has been granted the right not to apply the requirements of the 89-FZ on duties of regional operators to handle MSW in the city until January 1, 2022. The Government of Saint Petersburg made a decision to postpone to the implementation of waste management reformation in the city until July 1, 2021.

3 LIFE CYCLE ASSESSMENT OF THE MSW MANAGEMENT SYSTEM

3.1 The methodology of life cycle assessment

LCA is widely used for the evaluation of the environmental impact when solid waste management systems are studied (Banias et al., 2020; Hadzic et al., 2018; Silva et al., 2021). LCA in the waste sector may have several applications (Christensen et al., 2020). In its essence, the method allows to examine the environmental impact in the view of its various categories and to take into account all stages of the waste life cycle. Also, it is crucial that the influence of changes in the MSW management system can be studied through building different scenarios. Being a standardized method, LCA must follow the ISO 14040 (2018) and the ISO 14044 (2018).

MSW management system is multifunctional, meaning that it has several product outputs with a specific function. Since LCA always aims to identify the environmental impact associated with a single function of a system, the need to divide the impact between product outputs emerges. To tackle this issue, system expansion is generally used as a preferred option. The method of expanding the system involves consideration of additional processes, which provide functions irrelevant for the study. System expansion can be implemented in two ways: by adding those processes or by subtracting them (Matthews et al., 2014). They only differ in terms of the approach to the calculations but not the result of their application. In this study, system expansion by subtracting additional processes is used, which can also be referred to as the avoided burden or substitution approach.

The next aspect that may be specified is whether this study can be reckoned attributional or consequential. Attributional LCA estimates the impact that occurs generally as a part of global environmental impact. Consequential LCA also considers changes in this impact which may occur as a consequence of decisions made in the product system (Sphera et al., 2020). Also, the difference between these approaches can be regarded to the use of average or marginal data (Finnveden et al., 2009). While attributional LCAs are based on average technologies and resources, the consequential studies consider marginal effects, i.e. changes in feedstock sources and even technologies, when the product system influences a market.

Often, economic methods are involved to estimate these changes (Matthews et al., 2014). This study is limited to consideration of average effects though it is generally change-oriented, meaning that it estimates the impact of changes proposed to the product system. Therefore, this study cannot be firmly regarded as an attributional or consequential one as it has features of both types.

When calculating the impact assessment results for the product system, in some cases, the choice must be made regarding the use of long-term or short-term emissions. Generally, LCA is expected to consider all emissions related to the product system i.e. long-term emissions; while short-term emissions should only be used to study their influence on the results in a sensitivity analysis (Doka et al., 2003). Therefore, this study is based on data for long-term emissions when a choice must be made.

3.2 Goal and scope of the study

The study aims to analyze the current state of municipal solid waste management in the Leningrad region and Saint Petersburg and to compare it with the alternative scenarios proposed based on the European experience. It is intended to be applied as an instrument for decision making when the MSW management subsystem is developed in Saint Petersburg and the Leningrad region. Also, it can be used to educate and raise awareness regarding the environmental impact of operations in MSW management.

Impact categories considered in this LCA are global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), and abiotic resource depletion potential – fossil fuels type (ADP_f). Biogenic emissions are excluded from the scope of impact assessment so that only fossil GWP is assessed.

The scope of the studied system includes the entire life cycle of the waste following the “bin-to-grave” approach. It starts from waste generation, i.e. when citizens generate waste and put it into a rubbish bin, to its end-of-life. However, the study does not consider the transportation phase, even though the environmental impact of transportation may be substantial for the total performance of the system when it comes to acidification and eutrophication (Liikanen et al., 2018). The system boundary for the LCA is depicted in

Figure 9. It covers processes of MSW treatment as well as avoided production of energy and materials.

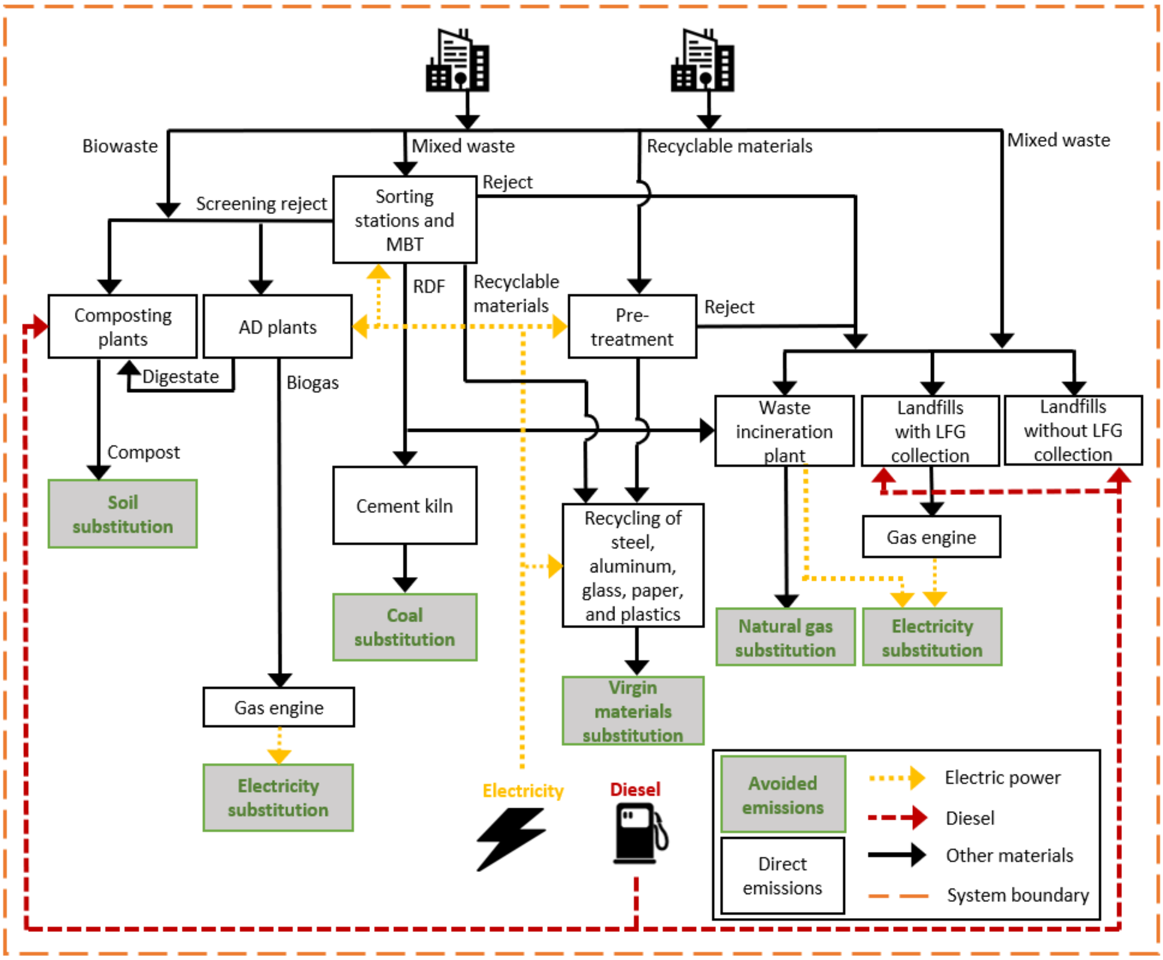

Figure 9. The system boundary of the study

As the MSW management system addresses waste handling, a function of this product system is to provide environmentally safe options for municipal solid waste management. The functional unit used in the modelling is the mass of MSW generated in the Leningrad region and Saint Petersburg annually, i.e. 3 075 970 tons of MSW in 2018. The annual generation of MSW used in the assessment is based on the statistical data from 2018 reported by the Government of Saint Petersburg (2019a) for Saint Petersburg and by the Federal Department of State statistics (2020) for the Leningrad region and given in Table 1 and Table 2. The growth of waste generation over time is not considered in the study.

Geographically, the analysis covers two federal subjects of the Russian Federation, namely Leningrad Region and the federal city of Saint Petersburg. This still may include waste processing outside of the regions, but generally, the study focuses on the waste generated and dealt with in the two regions.

Technological coverage includes existing infrastructure as the baseline, as well as possible new facilities according to the best available knowledge.

As for the time coverage, the current state of the system described refers to the year of the latest most detailed available statistics, which is mostly related to 2018. The first alternative scenario considers the changes in the system planned to achieve by 2024 through the reformation. Other scenarios describe the state of the system that can be reached further in the future.

Scenarios are built with step-by-step development of the system, i.e. each next scenario is based on the previous one with a new practice implemented. At the same time, scenarios are divided into two sub-scenarios to consider two options of biowaste treatment: composting and anaerobic digestion. The scenarios studied in this paper are presented further.

Scenario 0 – The baseline
MSW handling practices are in accordance with statistical data from 2018.
Scenario 1 – Development planned for 2024
Source separation of organic waste is implemented. New facilities operate in the Leningrad region: additional capacities for MSW sorting, composting, and RDF production.
Scenario 2.1 – Landfill gas collection – Composting of organic waste
The use of landfill gas collection is doubled compared to Scenario 1.
Scenario 2.2 – Landfill gas collection – Anaerobic Digestion of organic waste
The use of landfill gas collection is doubled compared to Scenario 1. Anaerobic digestion is used instead of composting for a part of organic waste.
Scenario 3.i.1 – Incineration of MSW – Composting of organic waste
Incineration of 850 000 tons of MSW is implemented.

Scenario 3.i.2 – Incineration of MSW – Anaerobic Digestion of organic waste
Incineration of 850 000 tons of MSW is implemented. Anaerobic digestion is used instead of composting for a part of organic waste.
Scenario 3.ss.1 – Source separation of recyclables – Composting of organic waste
Source separation of metals, glass, paper and cardboard, plastics is implemented.
Scenario 3.ss.2 – Source separation of recyclables – Anaerobic Digestion of organic waste
Source separation of metals, glass, paper and cardboard, plastics is implemented. Anaerobic digestion is used instead of composting for a part of organic waste.

The study is intended to be publicly available, and the target audience comprises of scientific community, citizens, administrators, businessmen, university staff, and other parties from the studied region and beyond.

3.3 Life cycle inventory analysis

In terms of the MSW composition, all studied scenarios are based on data from the Committee for the improvement of Saint Petersburg (2012) given in Table 3 and from AO “DAR/VODGEO” given in Table 4 (a) for Saint Petersburg and the Leningrad region respectively. Changes in MSW composition over time are not considered.

Amounts of waste involved in different treatment processes are given in Figure 10 for each scenario.

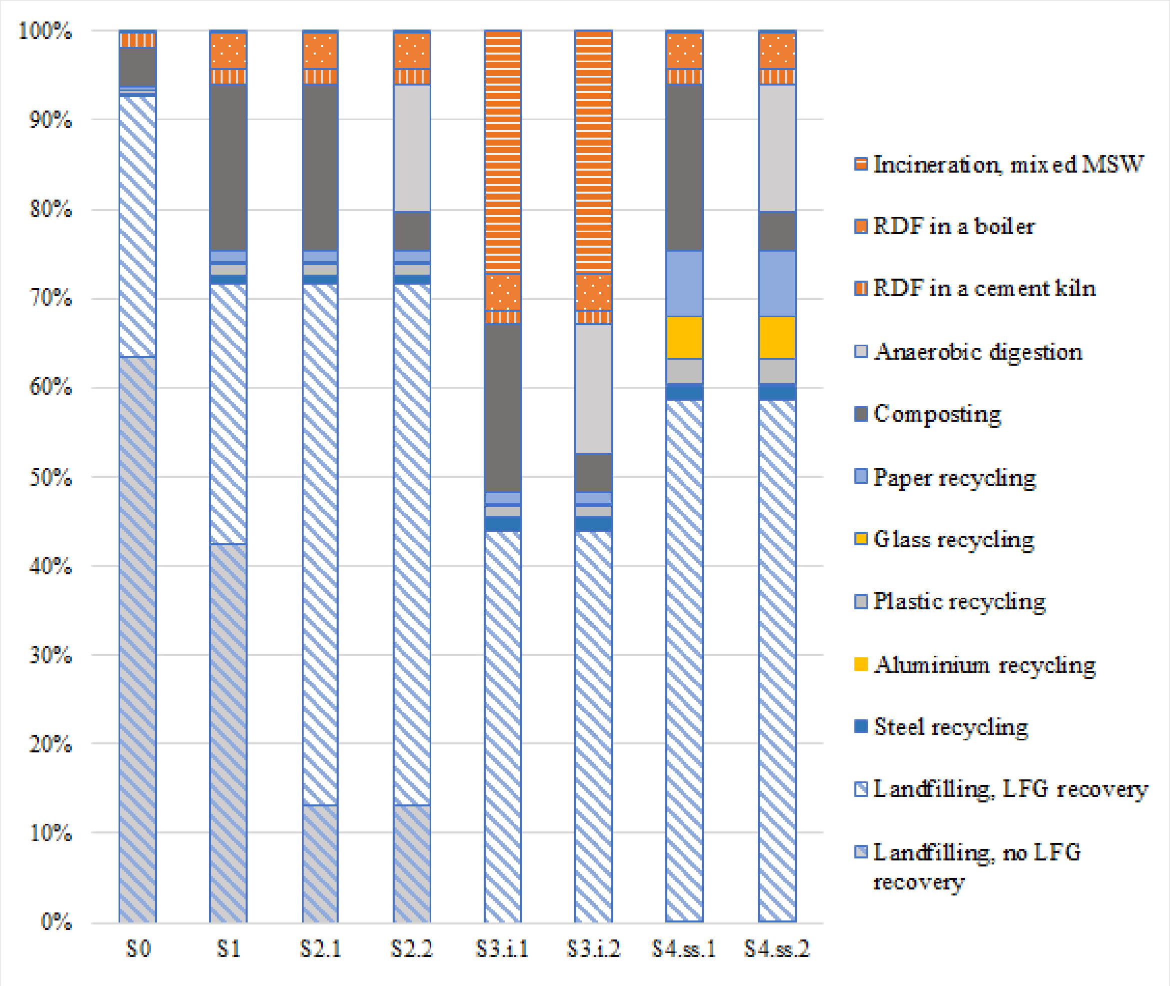

Figure 10. Distribution of waste amount by treatment methods for each studied scenario

3.3.1 Baseline scenario inventory data

As a baseline for the Leningrad region, 10% of generated MSW is processed in sorting stations (Federal Department of State statistics, 2020). According to the TWMS, Appendix 8, and Federal Service for Supervision of Consumer Rights Protection and Human Welfare (2020), the share of MSW sorted with separation of organic material equal 22%, while the rest is processed with no screening. The amount of waste recycled or otherwise utilized is calculated based on recovery rates for manual sorting, which are given further in this section. This results in waste flows depicted in Figure 11.

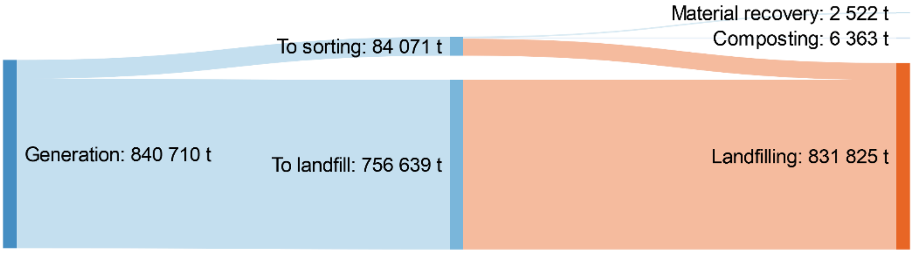

Figure 11. Flows of MSW in the Leningrad region used as a baseline

The baseline for Saint Petersburg is based on processing of 21% of generated MSW according to the data from 2018 given by the Government of Saint Petersburg (2019a). Several processing plants are considered operational in the city; detailed information on the processes and waste amount is presented in Appendix I. This results in waste flows depicted in Figure 12.

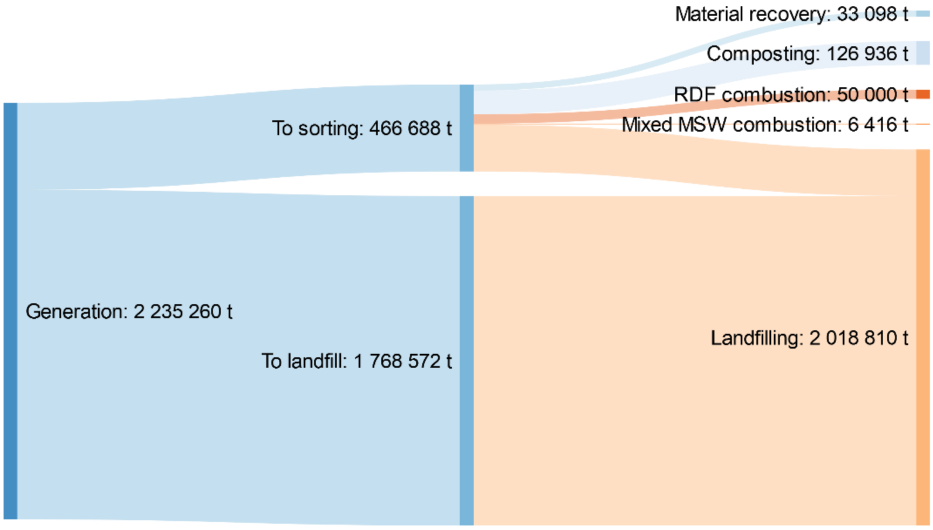

Figure 12. Flows of MSW in Saint Petersburg used as a baseline

In both cases, the list of separated recyclables includes paper and cardboard, glass, plastics, aluminum cans, and ferrous metals. The latter fraction is separated by a magnetic separator while other fractions are sorted out manually in most cases.

3.3.1.1 Automated sorting facility

The process of automated sorting refers to Staroobryadcheskaya and Predportovaya sorting stations in Saint Petersburg. Recovery rates for each fraction are given in Table 7. The amount of waste received for sorting is given in the Appendix I, 1.

Table 7. LCI data on automated sorting

Parameter	Value	Unit	Reference
Electricity consumption	70	kWh/ton$_{MSW}$	(Nasrullah, 2015)
Separation efficiencies			
Ferrous metals	39.5[a]	% of initial fraction mass	(OOO “KOSMOS,” 2016)
Aluminum cans	25.0[a]	% of initial fraction mass	(OOO “KOSMOS,” 2016)
Plastics	36.2[a]	% of initial fraction mass	(OOO “KOSMOS,” 2016)
Paper and cardboard	26.0[a]	% of initial fraction mass	(OOO “KOSMOS,” 2016)
Screening reject	34.4	% of input MSW	(OOO “KOSMOS,” 2016)
RDF	25.0	% of input MSW	(OOO “KOSMOS,” 2016)
[a] Calculated based on recovery rates from the referenced source and current MSW composition			

3.3.1.2 Sorting with manual separation of recyclable materials

Sorting with manual separation of recyclable materials can be done with or without separation of the organic fraction in a trommel screen depending on whether composting of screening reject is implemented at the facility. Thus, such sorting lines include a feed conveyor, a magnetic separator, a conveyor, a baler, and, in case organics is sorted out, a trommel screen. Electricity consumption of a line is calculated based on the equation and data given by Pressley et al. (2015).

The recovery rate for ferrous metals is assumed to be equal to one in the automated sorting line, as a magnetic separator is used in both cases. Recovery rates for fractions that are extracted from MSW manually were modified so that the overall recovery rate (including ferrous metals) equals 3%, which corresponds to data from MPBO-2 manual sorting (MPBO-2, 2018b). The LCI data on the sorting process is represented in Table 8.

The sorting with separation of compostable materials refers to the sorting implemented in MPBO-2 plant in Saint Petersburg, Lel' Eko sorting station in Kirishi, and the sorting station next to the landfill in Priozerskiy district in the LR. Sorting without separation of organics is modelled for Sinergiya facility and TEK sorting station in Saint Petersburg, and the rest of sorting processes in the Leningrad region.

Table 8. LCI data on sorting line with manual separation of recyclable materials

Parameter	Value	Unit	Reference
Electricity consumption			
Screen included	3.3	kWh/ton$_{MSW}$	(Pressley et al., 2015)
Screen excluded	2.5	kWh/ton$_{MSW}$	(Pressley et al., 2015)
Recovery rates			
Ferrous metals	39.5 [a]	% of initial fraction mass	(OOO "KOSMOS," 2016)
Aluminum cans	5.6 [a]	% of initial fraction mass	(Il'inykh et al., 2013)
Plastics	2.5 [a]	% of initial fraction mass	(Il'inykh et al., 2013)
Paper and cardboard	2.6 [a]	% of initial fraction mass	(Il'inykh et al., 2013)
Glass	5.7 [a]	% of initial fraction mass	(Il'inykh et al., 2013)
Screening reject	34.4	% of input MSW	(OOO "KOSMOS," 2016)
[a] Calculated based on recovery rates from the referenced source and an assumption that overall recovery rate equals 3%			

The information on OOO "TEK" from Federal Service for Supervision of Consumer Rights Protection and Human Welfare (2020) states that bulky waste is separated at the OOO "TEK" sorting station to be shredded and sent to the pyrolysis plant. Combustible MSW is separated for pyrolysis plant as well. Due to the absence of data on material balance for sorting station where waste for pyrolysis is separated, it is assumed that only bulky waste (wooden items) is sorted out for further pyrolysis and this accounts for 50% of waste recovered at the station. Then, total 2 436 tons of MSW, which are stated to be sent to utilization (Committee for the improvement of Saint Petersburg, 2020), comprise of 1 218 tons of bulky waste sent to the pyrolysis plant, 329 tons of paper and cardboard as well as 889 tons of steel scrap. These values are obtained based on the information that paper and steel waste are the only recyclable materials which are separated at TEK (Federal Service for Supervision of Consumer Rights Protection and Human Welfare, 2020) and the recovery rates for these fractions given in Table 8. Worth to mention is that these assumptions affect only total emissions from the system under study, as this process is present and identical in all scenarios.

3.3.1.3 Windrow composting

Treatment of biowaste in windrows refers to composting done at the landfill sites at the Novyy Svet landfill, Lel'-Eko landfill, the landfill in Priozerskiy district. Composition of screening reject obtained for further composting is based on data from the screening process at Staroobryadcheskaya (OOO "KOSMOS," 2016) and given in Table 9. Textile is assumed to contain 50% of biodegradable material. Screening reject less than 50 mm is assumed to contain three times more food, wood, paper, and textile waste comparing to their known percentages from Table 9. In this case, food waste, paper, wood, and textile amount in 45% of screening reject which is less than 50 mm in size, and 60% of the total screening reject fraction. Generally, such a share of organic matter corresponds to data from Di Lonardo et al. (2012).

As the majority of biodegradable waste in the undersize fraction consists of food waste, the data on decomposition process refers to food waste. Accordingly, the content of carbon and nitrogen is assumed to be equal 230 kg/t and 7 kg/t of wet waste respectively. The degradation rate for carbon and nitrogen is assumed to reach 66% and 30% respectively (Boldrin et al., 2009).

Table 9. Composition of screening reject subject to composting (OOO “KOSMOS,” 2016)

Waste fraction	Mass, t/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

Emissions of methane and nitrous oxide are assumed from the ranges reported in the literature on open composting of food waste: average or lowest values are selected to refer to the colder climate and poorer management of the composting process. Emissions of ammonia and non-methane volatile organic matter (NMVOC) are taken from Brazil's open composting case from Lima et al. (2018).

Leachate is assumed to be collected for moisturizing the waste in windrows so that no leachate enters the environment.

Compost output amounts to 0.6 tons per ton of input MSW (AO “DAR/VODGEO,” 2010) and is utilized as landfill cover due to its low quality. When the composting product is used as a landfill cover, soil excavation is avoided. The amount of needed material for landfill covering in the studied area is challenging to estimate, so produced compost is assumed to be fully utilized. Since it is the thickness of the isolation layer that is regulated in landfill operation, the needed volumes of compost and soil are equal. If soil and compost bulk densities are assumed to be equal to 1600 kg/m^3 and 400 kg/m^3 respectively, excavation of 4 tons or 2.5 m^3 of soil is avoided per each ton of compost used.

Table 10. LCI data on windrow composting

Parameter	Value	Unit	Reference
Diesel consumption	3	l/t_{waste}	(Lima et al., 2018)
Share of organic matter in screening undersize flow	50	%	Calculated
Compost output	60	%	(AO “DAR/VODGEO,” 2010)
Direct emissions from composting			
CH_4	1.5	% degraded C	(Boldrin et al., 2009)
N_2O	2	% degraded N	(Boldrin et al., 2009)
NH_3	83	% degraded N	(Lima et al., 2018)
NMVOC	2	kg/$t_{wet\ waste}$	(Lima et al., 2018)
CO_2 biogenic	90	kg/$t_{wet\ waste}$	(Boldrin et al., 2009)
Emissions from diesel combustion (wheel loader)			
CO	13	g/l_{diesel}	(LIPASTO, 2016)
HC	3.0	g/l_{diesel}	(LIPASTO, 2016)
NO_x	17	g/l_{diesel}	(LIPASTO, 2016)
SO_2	0.008	g/l_{diesel}	(LIPASTO, 2016)
CO_2-eq. (CO_2, CH_4, N_2O)	2673	g/l_{diesel}	(LIPASTO, 2016)

3.3.1.4 Rotating drum composting

Due to the need in the rotation of drums, the technology requires relatively high electricity consumption. According to project documentation (AO “DAR/VODGEO,” 2010), the technology of drum composting consumes 62.0 kWh energy and 0.013 m^3 water per ton of MSW.

After the active stage of composting in the rotary drums, curing of the compost occurs in windrows. The mechanical turning of the waste mass requires 0.71 l of diesel per ton of waste (Grzesik and Malinowski, 2017). The waste is then separated mechanically into compost fraction and ballast fraction.

An emission control system with 85% efficiency is known to be applied in the rotary drum (AO “DAR/VODGEO,” 2010). However, emission reduction is not accounted for in the study. The two-stage composting is modelled with overall emissions allocated to degradation of biomass in windrows; data on open composting emissions are given in Table 10.

Table 11. LCI data on rotary drum composting

Parameter	Value	Unit	Reference
Electricity need of a drum	62.0	kWh/t_{waste}	(AO “DAR/VODGEO,” 2010)
Water comsumption	0.013	m^3/t_{waste}	(AO “DAR/VODGEO,” 2010)
Organic matter content in the undersize waste flow	50	%	Calculated based on (OOO “KOSMOS,” 2016)
Diesel consumption for turning of windrows	0.71	l/t_{waste}	(Grzesik and Malinowski, 2017)
Compost output	19	%	(MPBO-2 phone interview, 2020)
Ballast output	75	%	
Direct emissions from composting	-	-	See Table 10

According to data provided by MPBO plant, the products of the process are compost (19% of composting input) used in landscaping and ballast (75% of composting input). The latter is considered stabilized waste and used for intermediate landfill covering. The other 6% are considered to be losses. Both compost and ballast are modelled to substitute soil, using the unit process “EU-28: Excavated soil with digger (EN15804 A5) ts” as a substituted one.

3.3.1.5 RDF incineration in a cement kiln

In the baseline scenario, RDF obtained via automated sorting in Saint Petersburg is incinerated in a cement kiln as stated by Bushikhin et al. (2015). LHV of RDF produced at Staroobryadcheskaya and Predportovaya stations equals 15.9-20.3 MJ/kg_{RDF} as received (Bushikhin et al., 2015). The composition of RDF is based on data from OOO “KOSMOS” (2016) and presented in Table 12.

Emissions of CO_2 reach 3.67 kg per each kg of fossil carbon as the ratio of their molar masses shows. Then, based on values from Table 12, CO_2 emissions from combustion RDF with such composition amount in 861 kg per ton of RDF. Emissions of sulfur dioxide and nitrogen oxides are based on data from Liikanen et al. (2018).

Table 12. Composition of RDF at Staroobryadcheskaya and Predportovaya plants and its fossil carbon content

Waste fraction	Content in RDF, %-w	Content of C fossil, % of a fraction mass
Paper, cardboard	42.7	0
Plastics	33.6	58
Tetra Pak	5.5	12[a]
Textile	10.2	25
Leather, rubber	3.2	25 [b]
Wood	4.8	0
Total	100.0	24
Reference	(OOO “KOSMOS,” 2016)	Calculated based on data from Havukainen et al. (2017)

[a] Based on the content of plastic in TetraPak equal 20%
[b] Based on carbon content in inorganic rubber

Emissions generated during combustion are treated in air pollution control (APC) units. Two flue gas cleaning technologies are considered in the study: lime scrubbing for sulfur dioxide removal and selective non-catalytic reduction (SNCR) for nitrogen oxides removal (Leme et al., 2014). However, solid residues from the APC unit are not taken into account in this thesis.

Table 13. LCI data on RDF incineration

Parameter	Value	Unit	Reference
LHV of RDF	15.9	MJ/kg_{RDF}	(Bushikhin et al., 2015)
Bottom ash output	15.7	% of RDF	(Bushikhin et al., 2015)
Fly ash output	4	% of RDF	(Consonni et al., 2005)
Emissions from RDF incineration before treatment			
CO_2 fossil	861	kg/t_{RDF}	Calculated
NO_x	2.3	kg/t_{RDF}	(Liikanen et al., 2018)
SO_2	1.7	kg/t_{RDF}	(Liikanen et al., 2018)

Table 14. LCI data on flue gases treatment

Parameter	Value	Unit	Reference
Lime consumption of a scrubber	6	kg/t_{RDF}	(Astrup et al., 2009)
NH_3 consumption of SNCR unit	2.75	kg/t_{RDF}	(Astrup et al., 2009)
Water consumption of APC	0.5	l/t_{RDF}	(Astrup et al., 2009)
NO_x emission reduction	50	%	(Zandaryaa et al., 2001)
SO_2 emission reduction	50	%	(Liu, 2005)
APC residues amount	5	% RDF input	(Astrup et al., 2009)

For ammonia and lime supply, GaBi processes “EU-28: Ammonia (NH3) production mix, without CO2 recovery (carbon dioxide emissions to air) ts” and “DE: Calcium hydroxide (Ca(OH)2; dry; slaked lime) (EN15804 A1-A3) ts” are used. Process water supply is modelled using the “EU-28: Process water ts” GaBi process.

Amount of bottom ash generated is assumed to constitute an average ash content of “Topal-1” RDF, which is stated to be between 14% and 17.3% (Bushikhin et al., 2015). When RDF is incinerated in a cement kiln, the bottom ash of RDF is incorporated in clinker and, therefore, does not require disposal. However, fly ash disposal is needed. The report on municipal solid waste incineration (MSWI) 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). Only in some cases, ashes are used in cement or other constructional material production (EkoSPES, 2020). Therefore, in this study landfill disposal of bottom ash and fly ash are modelled. Unit process “EU-28: Inert matter (Glass) on landfill ts” is used for this purpose.

The use of RDF in a cement kiln displaces the combustion of coal. The substitution ratio is calculated based on the energy content of these fuels. The energy content of hard coal from Russian deposits is on average 22.5 MJ/kg (Małkowski, 2018). The substituted process for coal acquisition is “RU: Hard coal mix ts” from GaBi database. Emissions for coal combustion are modelled based on data from the “RU: Process steam from hard coal 95% ts” GaBi process documentation.

3.3.1.6 Recycling of plastics

The study considers recycling of two types of plastics: polyethylene terephthalate (PET) and high-density polyethylene (HDPE). Content of PET and HDPE in recovered plastics is assumed based on the content of both materials in waste composition in Saint Petersburg (Table 3), which equals 3.4% and 1% respectively. Therefore, shares of PET and HDPE amount to 0.77 and 0.23 respectively.

General process of PET recycling is described in this paragraph. At the first stage of PET reprocessing, the received material is unbaled and shredded. Further, the process generally includes thorough sorting of flakes using mechanical separation of metals, near-infrared (NIR) technology, and manual sorting. For plastics from MSW washing is necessary, which is followed by separation of PET flakes in a float-sink tank and drying. The dried material is subject to air classification (elutriation) to remove possible residues from the stream. This stream of PET flakes may be screened to obtain particles homogenous in their size for further melting. After that, flakes pass through an extruder to reach even higher purity of material; the output of this process is PET pellets (or granules). The latter can be finally used to manufacture new materials, e.g. PET tape and new PET bottles. A similar process is applied for HDPE recycling, with possible differences in sorting technologies due to the higher density of polyethylene.

Worth mentioning is the fact that PET can be recycled with an omitted extrusion process when PET flakes are mixed with pellets of virgin plastic to produce new material. This is known to be applied in Russia to some extent, however, in this study, it is not considered.

In this study, life cycle impact assessment (LCIA) results of a “polyethylene terephthalate production, granulate, amorphous, recycled” unit process (rest-of-world location) are used to model PET recycling process. The process includes activities of PET reprocessing starting with receiving of sorted and baled PET material and requires 1.25 kg or sorted PET to produce 1 kg of PET granulate. Due to the absence of data on ADP_f in the ecoinvent database, this impact category is evaluated based on cumulative energy demand (CED) given in the database for this process.

A substitution ratio, which in theory reflects functional and physical correlations between primary and secondary products as well as their market demand, is assumed to be equal to 0.81 kg of virgin PET per kg of recycled PET in case of virgin plastic displacement (Rigamonti et al., 2010). Primary production of PET is modelled using the process “polyethylene terephthalate production, granulate, amorphous” from ecoinvent database 3.7. Outputs of both recycling and primary production processes are PET granulate.

For modelling of HDPE recycling, LCIA results of a “polyethylene production, high density, granulate, recycled” unit process (rest-of-world location) are used. The process includes activities of HDPE reprocessing starting with receiving of sorted and baled HDPE material and requires 1.06 kg or sorted HDPE to produce 1 kg of HDPE granulate. Furthermore, primary production of HDPE is modelled using “polyethylene production, high density, granulate” unit process from the ecoinvent database: values used are given in Table 18. Outputs of both HDPE production processes, based on raw and waste materials, are HDPE granulate. Substitution ratio equals 0.75 kg virgin HDPE / kg recycled HDPE according to (Gala et al., 2015).

3.3.1.7 Recycling of paper

As stated in Section 2.5.4, in Russia waste paper is mostly used to manufacture products of lower quality such as napkins, toilet paper, cardboard. Therefore, in this study, it is assumed to be used in tissue paper production.

Data for modelling were obtained from the ecoinvent process “tissue paper production, RoW”. This process is entirely based on the use of waste paper as raw material and requires 1.17 kg of waste paper to produce 1 kg of tissue paper.

Tissue paper, which is produced in this process, substitutes tissue paper manufactured from virgin materials. The substitution ratio is assumed to be 0.83 kg of virgin paper per kg of recycled paper according to Gala et al. (2015). In turn, the primary production process is based on the data for the ecoinvent process “tissue paper production, virgin, GLO”.

3.3.1.8 Recycling of metals

Recycling of steel and aluminum is considered in the study. In general, collected metal scrap substitutes virgin materials in the production of steel and aluminum. Similarly to other recyclable fractions, substitution of primary steel and aluminum occurs when metal scrap is recycled.

In the case of steel recycling, the environmental benefit of the process is assessed using credit for recycled steel. The credit quantifies the overall performance of the process by subtracting the impact of primary steel production from the impact of recycling. Besides, for this purpose theoretical processes are considered: a recycling process that uses 100% steel scrap and a primary production process based on 100% virgin feedstock (World Steel Association, 2017). The credit is modelled using the GaBi unit process “GLO: Value of scrap worldsteel” (database version 2020.2).

When it comes to aluminum recycling, the direct and avoided impacts are considered separately. The “EU28+EFTA+Turkey: Aluminium remelting: wrought alloys ingot from scrap (2015) European Aluminium <p-agg>” unit process is used to model recycling of aluminum scrap. Primary manufacturing of aluminum is modelled via the process “GLO: Aluminium ingot mix IAI (2010) IAI”. Besides, displacement of virgin aluminum by recycled one is based on a unit process “EU-15: Remelt aluminium ingots - credit (open loop) ts” from the GaBi database, which includes the substitution ratio equal to 0.69.

3.3.1.9 Glass recycling

Recycling of glass implies the use of glass cullet for partial substitution of virgin materials in glass production (Landi et al., 2019). It requires the processing of collected material to prepare it for melting alongside with conventional feedstock. Generally, it includes washing, drying, sorting, and milling of waste glass. Then glass cullet is melted and processed to form a product, e.g. a glass bottle.

First, 0.2 m^3 of water per ton of cullet is needed for washing of post-consumer glass. The maximum recycling process, i.e. the maximal substitution of virgin feedstock by glass cullet, requires 551 kWh of electricity and 6.96 GJ of thermal energy per each ton of glass cullet

(Greene, 2007). These values include energy consumption for the preparation of cullet for recycling and its further melting and forming. The inventory for glass recycling is given in Table 15.

Table 15. LCI for glass recycling

Parameter	Value	Unit	Reference
Water need for cullet washing	0.2	m^3/t_{cullet}	(Landi et al., 2019)
Electricity consumption	551	kWh/t_{cullet}	(Greene, 2007)
Heat consumption in melting	6963	MJ/t_{cullet}	(Greene, 2007)
Substitution ratio	1	kg virgin glass/kg recycled glass	(Rigamonti et al., 2010)

Avoided production of container glass is modelled using the ecoinvent unit process "packaging glass production, green, without cullet" (ecoinvent 3.7 database).

3.3.1.10 Landfilling of MSW

In the baseline scenario, the waste disposed of in landfills is divided into two flows: the majority of MSW is landfilled with no landfill gas (LFG) recovery, the minor part represents landfilling at Novyy Svet with the collection of LFG.

To calculate emissions of landfill gases, methane generation potential (kg_{CH4}/kg_{waste}) of waste decomposition is calculated based IPCC default model (IPCC, 2006a) 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.

Methane correction factor equal to 0.6 is used in modelling (IPCC, 2006a). This is a default value, which is related to unmanaged landfills at the same time. The use of a more specific MCF is challenging due to the limited data on landfilling conditions. The fraction of methane in LFG amounts in 50% as a default value suggested by IPCC. Further, the calculation is based on data given and referenced in Table 16. The calculated methane generation potential for degradable waste fractions are shown in Table 16 as well.

Table 16. Initial data for calculation of the methane generation potential

Waste fraction	DOC, kg_C/kg_{waste}	DOC_f, share	L, 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	(IPCC, 2006b)	(Lee et al., 2017)	Calculated

Shares of methane and other gases in LFG are assumed based on design documentation (ZAO NG - Energo, 2013) and given in Table 17. Emissions of other gases are further calculated based on the composition of LFG and CH_4 generation potential.

Table 17. Landfill gas composition

Gas component	Composition, % by volume		% by weight
CH4	35-65	50	28
CO2	30-45	45	70
CO	0-0,3	0,3	0,3
H2	1-5	4,1	0,3
O2	0-0,5	0,5	0,6
H2S	0,05-0,1	0,1	0,1
Reference	(ZAO NG - Energo, 2013)	Assumed	Calculated

Leachate generation rate is hardly possible to estimate, since there are many landfills in a studied region with possibly different features affecting the leaching process, but mainly due to the absence of data. In this study, leachate generation is assumed to amount in 0.2 kg per kg of MSW (Havukainen et al., 2017). The concentration of nitrogen and phosphorus in leachate is assumed according to Liikanen et al. (2018). According to available data reported in the previous chapter, in the studied region leachate is collected and used for moisturizing of waste masses with no leachate treatment. Above that, occurrent waste dumping means even a direct infiltration of leachate into the soil from some portion of MSW. Therefore, the baseline scenario is modelled with no treatment of leachate.

Table 18. LCI data on landfilling with no LFG collection

Parameter	Value	Unit	Reference
CH_4 oxidation factor	0.1	share	(IPCC, 2006a)
Emissions of LFG components			
CH_4	39.8	kg_{CH4}/t_{MSW}	Calculated
CO_2	98.4	kg_{CO2}/t_{MSW}	Calculated
CO	0.4	kg_{CO}/t_{MSW}	Calculated
H_2S	0.2	kg_{H2S}/t_{MSW}	Calculated
Leachate generation	0.2	t/t_{MSW}	(Havukainen et al., 2017)
P in leachate	13,95	mg/l	(Liikanen et al., 2018)
N in leachate	3,075	mg/l	(Liikanen et al., 2018)
Leachate density	1000	kg/m^3	Assumed
Diesel use	0.46	l/t_{MSW}	(Liikanen et al., 2018)
Emissions from diesel combustion (a bulldozer)			
CO	14	g/l_{diesel}	(LIPASTO, 2016)
HC	3.4	g/l_{diesel}	(LIPASTO, 2016)
NO_x	21	g/l_{diesel}	(LIPASTO, 2016)
SO_2	0.008	g/l_{diesel}	(LIPASTO, 2016)
CO_2-eq. (CO_2, CH_4, N_2O)	2674	g/l_{diesel}	(LIPASTO, 2016)

Landfill gas collection is considered at Novyy Svet landfill, which has an annual capacity of 900 000 tons of MSW. The value of LFG collection rate is assumed based on data from Doka (2003). Emissions from LGF combustion and flaring are assumed to be identical to those presented by Bacchi et al. (2018). The data for modelling of LFG collection is given in Table 21.

Table 19. Additional LCI data on landfilling with LFG collection

Parameter	Value	Unit	Reference
LFG collection rate	53	%	(Doka, 2003)
LFG to flaring	40	% LFG collected	(Liikanen et al., 2018)
Gas engine electric efficiency	36	%	(Liikanen et al., 2018)
Emissions from gas engine			
NO_x	11.6	g/Nm^3CH_4	(Bacchi et al., 2018)
CO	8.46	g/Nm^3CH_4	(Bacchi et al., 2018)
Emissions from flare device			
NO_x	0.631	g/Nm^3CH_4	(Bacchi et al., 2018)
CO	0.737	g/Nm^3CH_4	(Bacchi et al., 2018)
CH_4	1	% CH_4 input	(Bacchi et al., 2018)
Efficiency of flaring	99	%	(Liikanen et al., 2018)

In calculations related to LFG combustion, methane density equals to 0.657 kg/m^3 and methane LHV equals to 50 MJ/kg. Recovered energy from LFG combustion displaces primary electrical energy production, modelled with “RU: Electricity grid mix 1kV-60kV ts” unit process from GaBi.

3.3.1.11 Thermal treatment of MSW

According to the TWMSs of the studied regions, 6316 tons of MSW is utilized in the pyrolysis plant and 100 tons of MSW is incinerated in the Leningrad region (Waste Management Committee of the Leningrad Region, 2019a). Due to the insufficiency of data on the pyrolysis process, the waste is modelled to be incinerated, so that the total amount of incinerated MSW equals 6416 tons in the baseline scenario.

Before the waste is fed to the incinerator, ferrous metals are removed by a magnetic separator and then sent to recycling. The efficiency of separation corresponds to that at the sorting stations and is given in Table 7; the same applies to the electricity consumption of the process. Then, the incineration process is modelled separately for several waste fractions using the following unit process from the GaBi database:

- “EU-28: Waste incineration of biodegradable waste fraction in municipal solid waste (MSW) ELCD/CEWEP <p-agg>”,
- “EU-28: Waste incineration of paper fraction in municipal solid waste (MSW) ELCD/CEWEP <p-agg>”,
- “EU-28: Waste incineration of plastics (unspecified) fraction in municipal solid waste (MSW) ELCD/CEWEP <p-agg>”,
- “EU-28: Waste incineration of textile fraction in municipal solid waste (MSW) ELCD/CEWEP <p-agg>”,
- “EU-28: Waste incineration of ferro metals ELCD/CEWEP <p-agg>”,
- “EU-28: Waste incineration of untreated wood (10.7% H2O content) ELCD/CEWEP <p-agg>”,
- “EU-28: Waste incineration of glass/inert material ELCD/CEWEP <p-agg>”.

Thermal treatment of MSW is assumed to occur with energy recovery, which includes the production of both electricity and heat. The efficiencies of electricity and heat production, which are used in those GaBi unit processes, are based on data for European waste-to-energy plants from 2007-2010 (Dieter and Reimann, 2012). On average, i.e. for mixed MSW, they account for 15% for electricity production and 37.1% for heat production. Production of energy in MSW incineration results in substitution of primary electricity and heat in the regions. The processes used to model primary energy sources are “RU: Electricity grid mix 1kV-60kV ts” and “RU: Process steam from natural gas 90% ts”.

3.3.1.12 Energy supply

Russian electricity generation is largely based on natural gas as an energy source, as well as nuclear, hydro, and coal. According to BP (2019), in 2018 the share of natural gas in electricity generation was equal to 47%, while shares of nuclear and hydropower account for 18% and 17%, respectively. For modelling of electricity supply in GaBi, the unit process “RU: Electricity grid mix 1kV-60kV ts” is used. The electricity mix in this unit process is based on data from 2016, which is aligned with more recent data.

Thermal energy production in the regions mostly relies on natural gas as an energy source. In Saint Petersburg, the remaining coal and oil-based capacities are currently being substituted by natural gas-based heat generation (Government of Saint Petersburg, 2020c). Therefore, the production of thermal energy is modelled based on natural gas as a source in this study. The unit process used for this purpose is “RU: Process steam from natural gas 90% ts” from GaBi database.

3.3.2 Scenario 2024

All waste processing facilities from the baseline scenario are present in the Scenario 2024, but additional processes are modelled. Additional facilities for MSW processing and separate collection of an organic waste fraction represent the plans for the development of the system.

As the data on the development of the MSW processing infrastructure in the two regions is not compatible, a number of assumptions have to be done to model the future situation. First of all, in this study, the development of the infrastructure planned in the Leningrad region is considered over the one planned in Saint Petersburg. The reasons for such a decision are mentioned in section 2.6.2.

According to section 2.6.1 of the thesis, facilities planned by the LR are the Gatchina waste processing plant with the annual capacity of 500 000 tons of MSW and Kingisepp plant with the capacity of 300 000 tons/a. More detailed data on these facilities are given in section 2.6.1.

Construction of these plants would result in a total processing capacity of over 880 000 tons of MSW in the Leningrad region, including already existing facilities. Their operation would allow to reach targets for MSW processing and utilization in both Leningrad region and Saint Petersburg by 2024. Given the existing interconnection of waste management systems of regions, it can be expected that some portion of MSW from Saint Petersburg could be processed in the Leningrad region. This study assumes that Gatchina sorting plant is used to process MSW from Saint Petersburg, meaning that 500 000 tons of MSW are sent to the Gatchina plant from Saint Petersburg. This would expand the processing to 966 688 tons of MSW generated in Saint Petersburg, which results in 43% of MSW being processed. In the

Leningrad region, an additional capacity of Kingisepp processing plant would raise the share of processed MSW to 46%, while the target is 41% in 2024.

Some simplifications were used to model waste processing plants in Kingisepp and Gatchina. First, automated sorting at Gatchina MSW processing facility is modelled identically to Staroobryadcheskaya sorting station in Saint Petersburg: the data are given in Table 7. Manual sorting at Kingisepp waste processing station is modelled according to manual sorting in the baseline scenario (Table 8). The general data for modelling of additional processing plants are summarized in Table 22.

Table 20. Facilities modelled in the Scenario 2024

Facility	Capacity, tons/year	Sorting technology	Composting technology	RDF production
Gatchina waste processing plant	500 000	Automatic	Windrows	Yes
Kingisepp waste processing plant	300 000	Manual	Windrows	No

Production of SRF, which is planned at Gatchina plant, is modelled as RDF production with the following incineration of RDF in boilers at a waste incineration plant. Electrical energy is assumed to be recovered from RDF incineration and to substitute primary sources of electricity. The efficiency of power production is based on data from Leme et al. (2014) and equal to 18%. Displaced electricity is the Russian grid mix, modelled via “RU: Electricity grid mix 1kV-60kV ts” GaBi process. The use of natural gas in the amount of 1.9 m^3 per ton of RDF is needed as an auxiliary fuel in the incineration process (Astrup et al., 2009). Natural gas supply is modelled using the unit process “FI: Natural gas mix ts”, as it is based on 100% Russian feedstock and has a similar transportation distance. For unit conversion, the density of natural gas equal to 0.7 m^3/kg is used. Besides, when RDF is used as a fuel for boilers, the need for bottom ash disposal exists. In this study, bottom ash is assumed to be disposed of in a landfill alongside with fly ash as described earlier for the cement kiln case. Other than that, the modelling of the process is based on data from Table 13 and Table 14.

Source separation of biowaste is modelled as well according to the TWMSs in this scenario. Capture rate of biowaste, i.e. the share of biowaste put to a separate bin from total content of organic waste in MSW, is assumed to reach 16% according to average EU performance (Seyring et al., 2015). Also, 30% of contamination of biowaste is assumed.

To treat biowaste, windrow composting is most likely to be used as this practice is the most developed in the studied region. Besides, separately collected biowaste is assumed to be composted alongside with the screening reject while the practice is not yet fully and properly followed. Thus, low-quality compost is produced from the feedstock. This would have no difference from a one-bin collection system, except for possibly a higher recovery rate for recyclables due to their lower contamination. However, this factor is not considered in the study. In this scenario, the process of composting is modelled according to the data from Table 10.

The amount of MSW that undergoes landfilling is subsequently lower than in the baseline scenario, as a larger quantity of waste is processed. However, LFG collection is assumed to be used for the same amount of landfilled MSW similarly to the baseline scenario.

3.3.3 Anaerobic treatment of organic waste

Anaerobic digestion of organic fraction of waste is modelled as a sub scenario for cases, which consider additional technologies or practices for MSW handling (Scenario S2.2, Scenario S3.i.2, Scenario S3.ss.2). It is only applied to the additional amount of organic waste separated according to the plan of the development of the system by 2024 (Scenario S1), i.e. to source-separated organic fraction and screening reject at the new Gatchina and Kingisepp plants. Screening reject that is separated in the baseline scenario is modelled to be composted.

The composition of waste subject to anaerobic treatment is described in Table 9. Initial humidity of waste is assumed to reach 45% (Pan and Voulvoulis, 2012), while in the reactor it equals 90% (Havukainen et al., 2017). The methane generation and the content of totals solids are based on data from Pantini et al. (2015). These values are applied to the organic fraction of the screening reject, which is calculated based on the content of input flows as it is done for the composting process.

Emissions from the biogas production stage are assumed based on data for large-scale biogas production from Börjesson and Berglund (2006) for the mesophilic process. Losses of methane are assumed to be negligible and are not considered in the inventory. The biogas is assumed to be used for power and heat production. The electricity is supplied to the network and substitutes the avarage Russian grid mix. Heat is assumed to be used for heating of the reactor and replace the same amount of locally produced heat. Efficiencies of heat and power production are assumed to account for 40% each (Havukainen et al., 2017). These and other parameters of the anaerobic digestion process are represented in Table 21**.**

Table 21. LCI data on anaerobic treatment of organic waste

Parameter	Value	Unit	Reference
Initial humidity	45	%	(Pan and Voulvoulis, 2012)
Humidity at field capacity	90	%	(Havukainen et al., 2017)
Total solids (TS) content	55	%	(Pan and Voulvoulis, 2012)
Methane generation rate	0.129	Nm^3/kg_{TS}	(Pantini et al., 2015)
Electricity consumption	0.07	MJ/kg_{waste}	(Börjesson and Berglund, 2006)
Electric efficiency of biogas combustion	40	%	(Havukainen et al., 2017)
Efficiency of heat production	40	%	(Havukainen et al., 2017)
Emissions from biogas combustion			
NO_x	46.0	g/t_{OW}	(Börjesson and Berglund, 2006)
CO	11.0	g/t_{OW}	(Börjesson and Berglund, 2006)
SO_2	1.7	g/t_{OW}	(Börjesson and Berglund, 2006)
HC	3.0	g/t_{OW}	(Börjesson and Berglund, 2006)
CH_4	4.0	g/t_{OW}	(Börjesson and Berglund, 2006)
Electricity need in dewatering	4.4	kWh/t_{input}	(Karunanithi, 2014)
Efficiency of TS separation in dewatering	61.7	%	(Moller et al., 2002)
TS content in dried digestate	30	%	(Moller et al., 2002)

3.3.4 Landfill gas recovery

Scenarios 2.1 and 2.2 are built to investigate the effect of LFG collection on the environmental performance of the MSW management system. Additionally to the baseline, this scenario incorporates the collection of LFG from an equal amount of MSW. As a result, the total amount of 1 800 000 tons of MSW is disposed of with LFG recovery. Parameters for modelling of the process are identical to those used in the baseline scenario and given in Table 16, Table 17, and Table 19.

3.3.5 Incineration of waste

Scenarios S3.i.1 and S3.i.2 introduce additional mass burn incineration of MSW in the studied area. The amount of incinerated waste that is added in these scenarios is based on an average share of MSW sent to incineration in the EU. According to Scarlat et al. (2019), an average share of MSW incineration accounted for 27% in 2015. In the Leningrad region and Saint Petersburg, this would mean incineration of approximately 850 000 tons of MSW annually. This gives additional 650 000 tons of MSW to the amount of waste that is incinerated in previous scenarios. Then in these scenarios, 200 000 tons of waste generated in the Leningrad region and 450 000 tons generated in Saint Petersburg are assigned to thermal treatment. The process of MSW incineration is modelled identically to one is the baseline scenario.

3.3.6 Source separation

The environmental impact of source separation of recyclable materials is assessed by scenarios S3.ss.1 and S3.ss.2. A separate collection of metals, glass, plastics, paper and cardboard is assumed. Organic waste is collected separately as well as scenario 1 suggests.

Collection of these fractions is modelled using capture rates, which represent the shares of the generated amount of specific materials that are separated at source. The scenario refers to the average values of capture rates reported for capitals in the EU (Seyring et al., 2015). Besides, contamination of separately collected waste is assumed to reach 30%. Overall, the data on source separation of all five fractions, including biowaste, is given in Table 22.

Table 22. LCI data on implementation of source separation

Parameter	Value	Unit	Reference
Capture rate			
Glass	44	%	(Seyring et al., 2015)
Metals	16	%	(Seyring et al., 2015)
Plastics	12	%	(Seyring et al., 2015)
Paper and cardboard	36	%	(Seyring et al., 2015)
Biowaste	16	%	(Seyring et al., 2015)
Contamination rate	30	%	Assumed

Similarly to material recovery at sorting facilities, steel and aluminum are assumed to be collected as metals, while the collection of PET and HDPE is assumed for plastics fraction. Equal capture rates for aluminum and steel scrap is applied. The same way source separation of PET and HDPE is modelled.

Currently, there are several paths to organize the sorting of separately collected fractions before recycling. First, source-separated waste can be accumulated by recyclable material collectors and after some pre-treatment sent to recyclers. Also, it can be sent directly to recyclers with no additional sorting if the amount of impurities is negligible. Otherwise, separately collected waste may undergo the same sorting process as unsorted MSW due to the high content of impurities in collected material. In this study, it is assumed that source-separated waste is sorted before recycling so that 70% of the waste stream is separated as clean and suitable for recycling. The remaining 30% of the mass is mixed waste that is subject to landfilling.

3.4 The methodology of sensitivity and scenario analyses

The sensitivity analysis and scenario analysis are conducted in this study. To quantify how much the results change with the variation of a parameter, their sensitivity coefficients (SC) are calculated using the following equation (Bisinella et al., 2016):

$$SC = \frac{\Delta\, result}{\Delta\, parameter}.$$

In scenario analysis, not parameters but larger changes in the model are tested. For example, the influence on results from production of thermal energy based on coal instead of natural gas can be investigated. To quantify variations of LCIA results in scenario analysis, their relative sensitivity is calculated using the following equation:

$$Relative\ sensitivity = \frac{Modified\ result - Initial\ result}{Initial\ result}.$$

4 RESULTS AND DISCUSSION

The results of the assessment are provided within LCIA phase of the LCA. Four impact categories are considered in this study, including GWP, EP, AP, and ADP_f. All of them were calculated using CML 2001 impact assessment method introduced by Guinée et al. (2002). The latest version of the method available in GaBi and which was used in the study is from August 2016.

4.1 Contribution analysis

In order to present the results of LCIA, the environmental impact of the system in each scenario is disaggregated, so that impacts of each process can be seen from the diagram. This approach is known as contribution analysis. The results for GWP, EP, AP, and ADP_f are depicted in Figure 13, Figure 14, Figure 15, Figure 16, respectively.

Landfills are the largest contributors to climate change as can be seen from Figure 13, and that is one of the reasons to reduce the rate of landfilling in the MSW management system. In this study, a number of assumptions have been made to assess the impact of landfilling in the area; some of them are considered in the sensitivity analysis. According to the results (Appendix II, 1), 180-190 kg of CO_2-eq are emitted per ton of MSW when all waste is landfilled with LFG collection. This is close to the data from Manfredi et al. (2009) – 300 kg of CO_2-eq/ton for conventional MSW landfills – and Lima et al. (2018) – 250-450 kg CO_2-eq/ton when LFG collection is applied. The difference may occur primarily due to other LFG collection conditions.

In terms of GWP, material recovery is beneficial. Even though the recycling of paper results in a significant amount of direct emissions, the substitution of virgin tissue paper on the market gives a negative net GWP. Production of 1 kg of tissue paper from wastepaper prevents the release of 1.1 kg CO_2-eq. The net impact results for each impact category and separate processes can be found in Appendix II. Given also large amount of wastepaper in MSW composition, the impact of paper recycling results in the most significant savings of greenhouse gases in the system. According to Appendix II, the recycling of metals and plastics is most favorable for the system. Particularly, recycling of aluminum shows the highest efficiency of GWP reduction, as it saves 10.4 kg CO_2-eq per one kg of recycled material. Steel and plastics recycling is associated with the savings of 1.6 and 1.7 kg CO_2-eq per each kg of recycled material, respectively. However, the potential for GWP reduction in the MSW management system generally depends on the waste composition and the efficiency of separation of specific materials. In this case-study, recycling of paper and plastics allows the most significant reduction of GWP of the system.

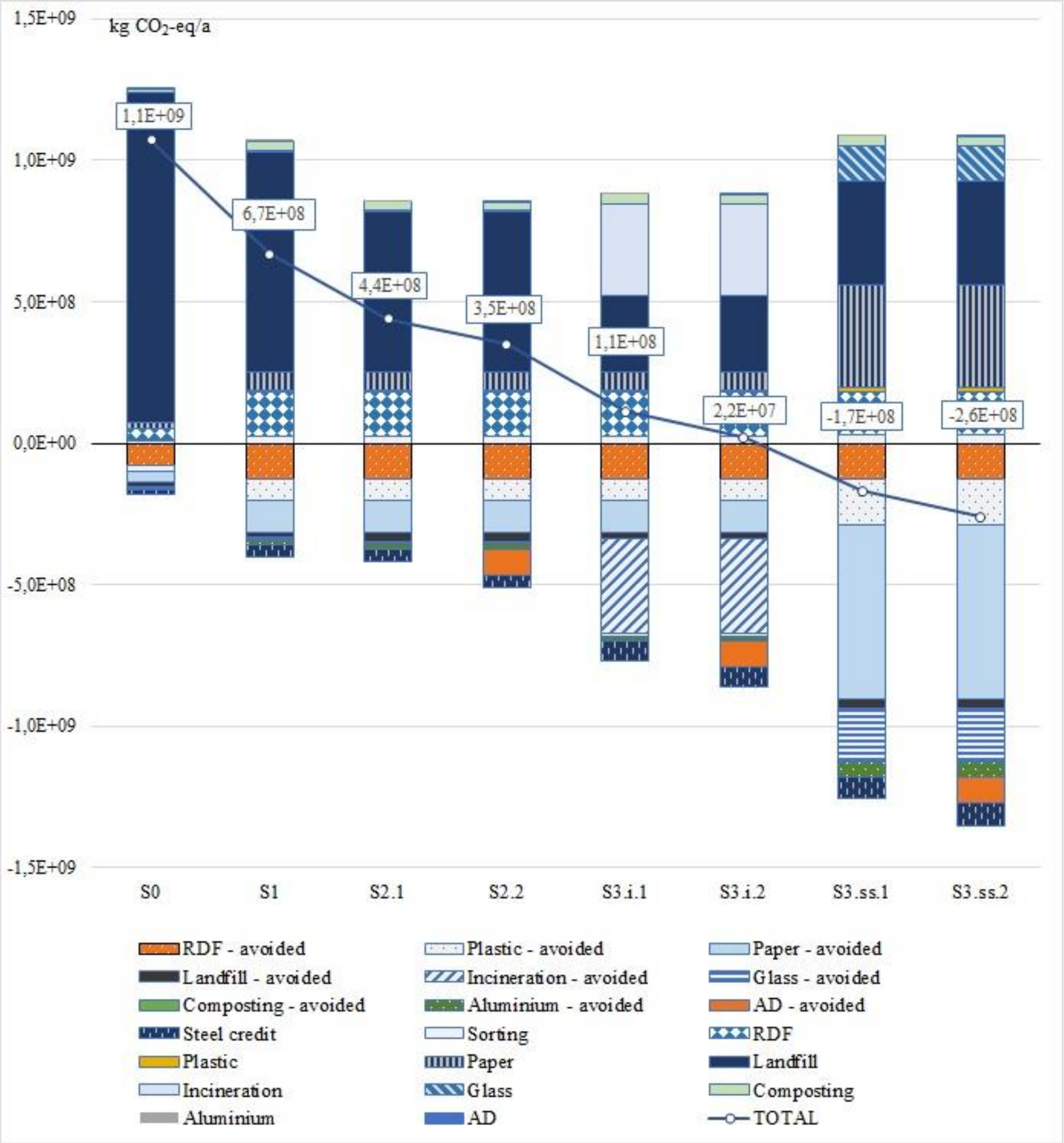

Figure 13. Global warming potential of the studied MSW management system by scenarios: S0 – the current situation, S1 – planned development by 2024, S2 – LFG collection doubled, S3.i – incineration of mixed MSW is added, S3.ss – source separation is added (subscenario 1 – composting of organic waste, subscenario 2 – AD of organic waste)

The performance of organic waste treatment was assessed for both aerobic and anaerobic processes, i.e. composting and anaerobic digestion. Composting resulted in a positive GWP, while it is still beneficial for climate change mitigation as an alternative for MSW landfilling. Particularly, in the baseline scenario, the net GWP of landfilling amounts to 0.4 kg CO_2-eq per kg of MSW, and the same figure for composting is equal to 0.06 kg CO_2-eq per kg of composted waste. As an important remark, the net impact of composting is commonly lower when the compost substitutes fertilizers or growth media (Boldrin et al., 2009), so higher quality of compost could further contribute to climate change mitigation. Furthermore, AD of screening reject and separately collected organic fraction (in scenarios S2.2, S3.i.2, S3.ss.2) contributed to the GWP reduction significantly. This is due to the electricity and heat substitution, which are mostly fossil-based products in Saint Petersburg and the Leningrad region. In conclusion, the results indicate that organic waste can significantly reduce GWP of the system if used in biogas production. Also, the potential of good-quality compost production to decrease GWP should be studied.

Incineration of mixed MSW saves 0.19 kg CO_2-eq per kg of MSW according to Appendix II, 1. However, the net result is highly dependent on the source of the substituted energy. This is especially important when it comes to the substitution of heat and it is considered in scenario analysis further in the thesis. For the RDF incineration, the overall results showed positive GWP (0.16 kg CO_2-eq/kg of MSW). RDF utilization in a cement kiln (the result can be seen for RDF incineration in the baseline scenario individually) is, however, negative and equal to -0.7 kg CO_2-eq/kg of MSW. It is important to say, that such a value influences the total result for RDF heavily and reveals that RDF incineration in a boiler is not favorable comparing to landfilling. This may result from the way the energy substitution was assumed: production of electricity only with the efficiency equal to 18%.

With regard to EP, the contribution of the processes differs significantly. However, similarly to GWP, results in Figure 14 show that the production of tissue paper from both waste and virgin materials are the largest contributors to eutrophication from the MSW system. It determines the increase of EP in Scenario 1 with the increase of paper recycling. Also, the composting process has a substantial effect on EP. Generally, only landfilling and composting have a positive EP according to Appendix II, 2. Due to the magnitudes of EP of metals, plastics, paper and cardboard, and glass recycling, the total result is mostly determined by the recycling rates. Therefore, a sharp drop of the total EP occurs in the last scenarios which include source separation of MSW.

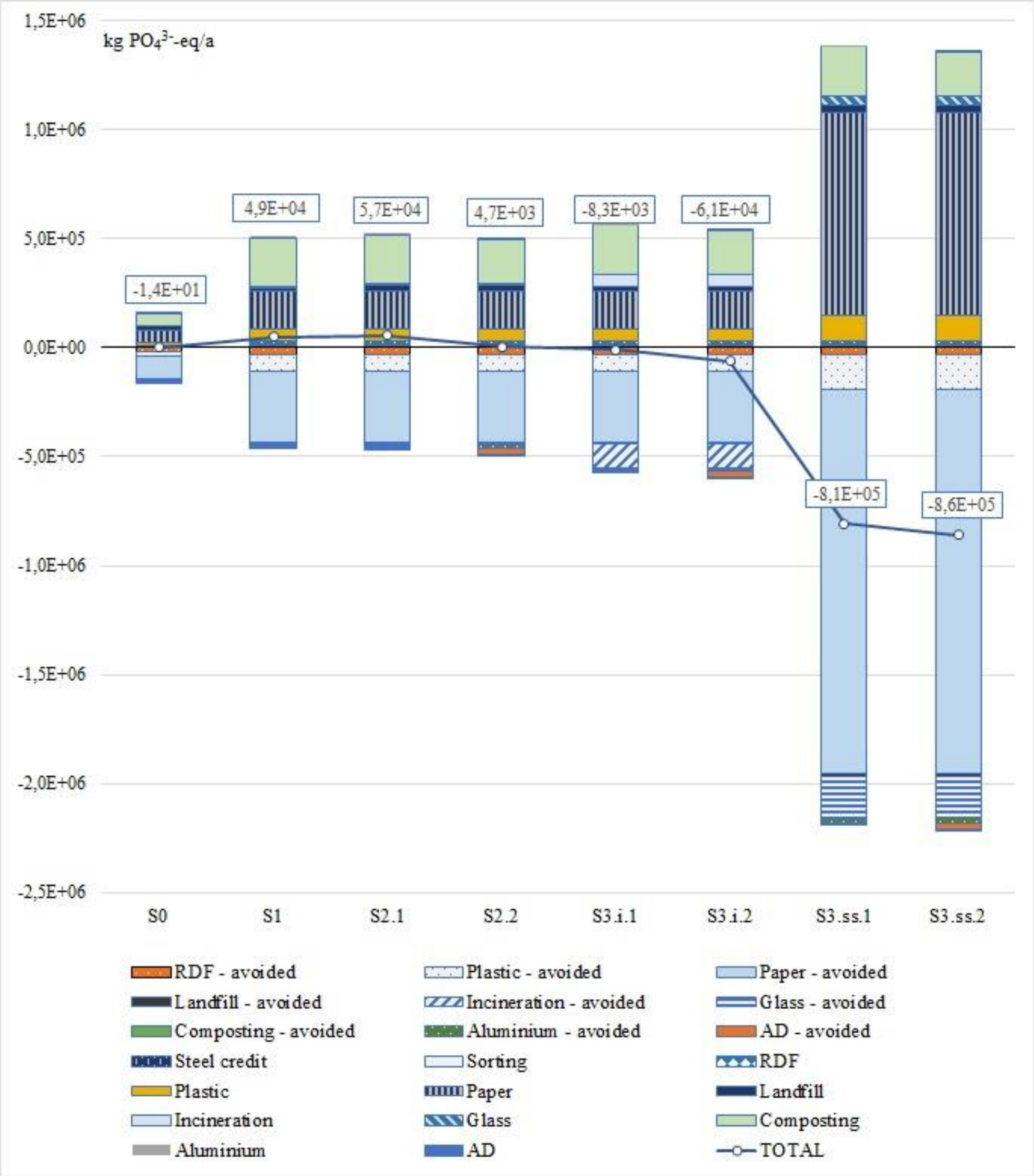

Figure 14. Eutrophication potential of the studied MSW management system by scenarios: S0 – the current situation, S1 – planned development by 2024, S2 – LFG collection doubled, S3.i – incineration of mixed MSW is added, S3.ss – source separation is added (subscenario 1 – composting of organic waste, subscenario 2 – AD of organic waste)

Composting of the organic fraction is also an important contributor to direct acidification, as shown in Figure 15. Its net impact is positive and equal to 1.8 g SO_2-eq. per kg of waste and is higher comparing to the AP of landfilling (0.1 g SO_2-eq. in the baseline scenario). In contrast, anaerobic treatment of organic fraction prevents the acidification associated with energy production. Besides, with the implementation of source separation practices, the influence of material recycling, primarily paper recycling, further decreases AP. RDF incineration influences AP significantly due to substitution of coal combustion in the cement kiln. Overall, the trend of AP change over different scenarios resembles the one for GWP.

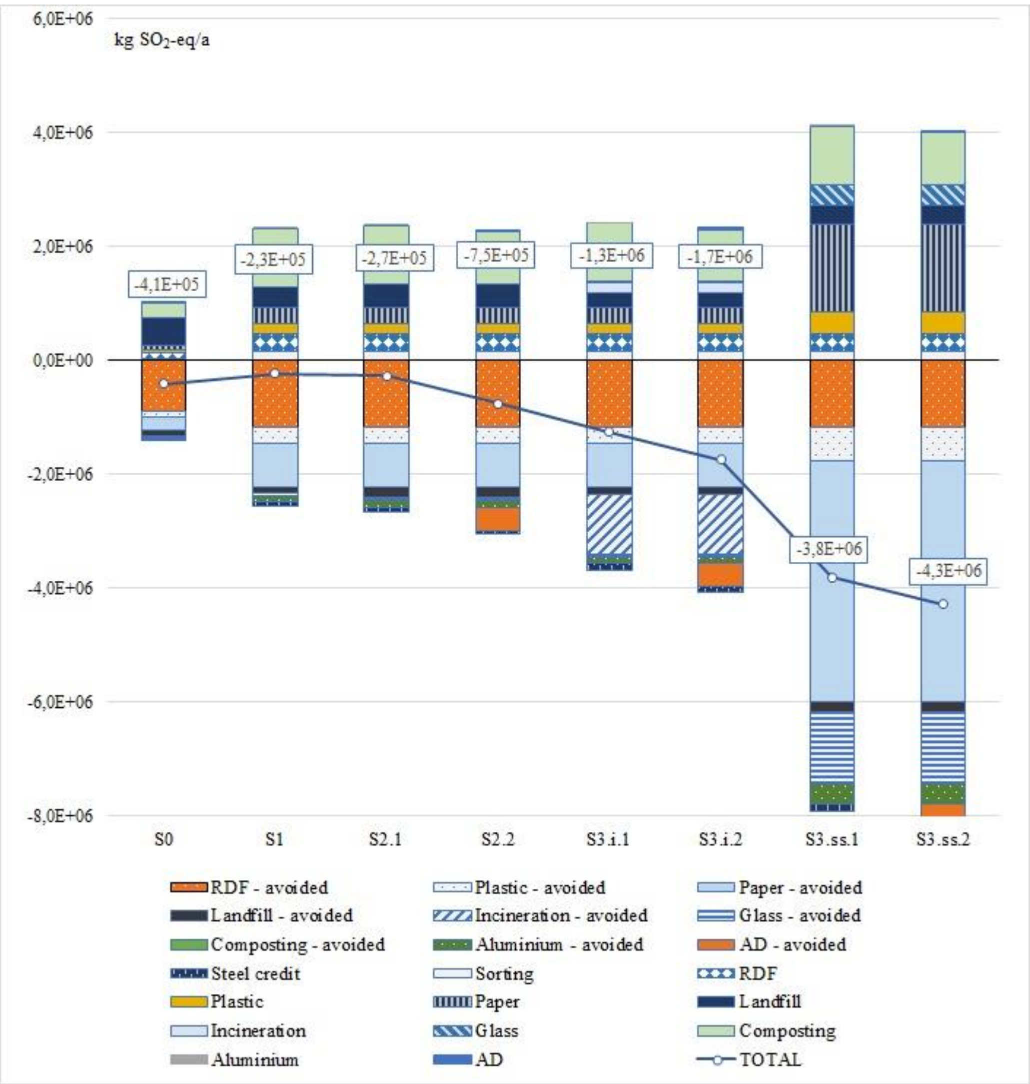

Figure 15. Acidification potential of the studied MSW management system by scenarios: S0 – the current situation, S1 – planned development by 2024, S2 – LFG collection doubled, S3.i – incineration of mixed MSW is added, S3.ss – source separation is added (subscenario 1 – composting of organic waste, subscenario 2 – AD of organic waste)

Recycling of paper, plastic, and glass contribute the most to direct depletion of fossil resources (Figure 16). However, RDF incineration, i.e. replacement of coal combustion primarily, makes ADP$_f$ result negative even in the current state of the system. The production of energy from mixed MSW further reduces the impact in scenarios 3.i. Incineration of waste and AD contribute to ADP$_f$ reduction most significantly also because of the large amount of waste used in these processes. At the same time, recycling processes have a slighter effect on ADP$_f$ reduction, even though their specific net results are the highest (Appendix II, 4).

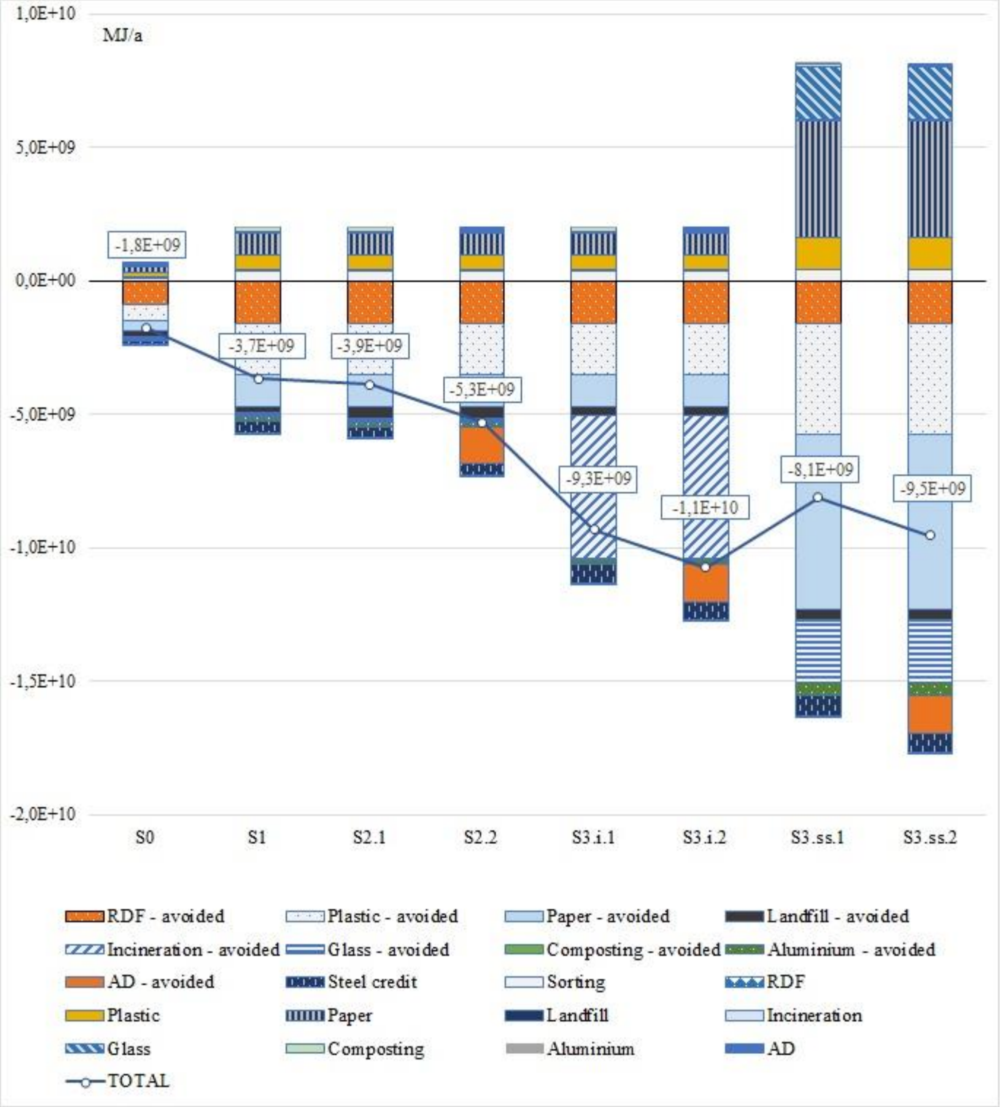

Figure 16. Abiotic depletion potential (fossil fuels) of the studied MSW management system by scenarios: S0 – the current situation, S1 – planned development by 2024, S2 – LFG collection doubled, S3.i – incineration of mixed MSW is added, S3.ss – source separation is added (subscenario 1 – composting of organic waste, subscenario 2 – AD of organic waste)

Overall, the results show the reduction of the environmental burden of the MSW management system as the system develops. The improvements which are planned by 2024 under the reformation of the system are expected to reduce the impact on climate change and fossil resource depletion. This is due to both the decrease of the direct impact, i.e. emissions from waste decomposition at landfills, and the increase of avoided impact.

Following the practice of source separation at the average EU level showed the most substantial effect on most of the impact categories (GWP, EP, AP). While less significant benefit is gained by MSW incineration, this technology contributes a lot to the reduction of resource use (Figure 16). Besides, one advantage of MSWI plants over source separation is that it can be an efficient measure of landfilling reduction in a much shorter time period.

It is important to keep in mind that this LCA covers only four impact categories, thus, it provides a limited view of the environmental impact of the MSW system. Other impact categories, e.g. ecotoxicity, may be a substantial indicator of the performance of the system. Poor practices of hazardous MSW collection, which are known to currently prevail in the studied area, lead to high rates of its landfilling and severe contamination of the environment by heavy metals. Besides, a high level of hazardous materials contaminates the feedstock for compost production, restricting its use as a fertilizer and possible benefits of it for other impact categories.

4.2 Sensitivity analysis

In this study, sensitivity analysis is conducted regarding the parameters of MSW landfilling. Given the amount of MSW landfilled in the studied area, it may influence the total impact of the system significantly. First, LFG collection rate is uncertain in this study due to the absence of site-specific data. The sensitivity of the results is checked when LFG collection rate is assumed to be 50% lower and 50% higher than the initially assumed value. Being equal to 53% initially, the landfill gas collection rate is changed to 27% and 80% for the sensitivity analysis. The results are represented in the form of sensitivity coefficients, which are equal for both cases of LFG collection rate change and given in Table 23. Within each impact category, SCs vary depending on the amount of landfilled waste. For example, variation of GWP result is the highest in scenario 2, where the amount of waste landfilled with LFG collection is the largest. The relative changes in results can be seen further in Figure 17, Figure 18, Figure 19, and Figure 20.

Table 23. Sensitivity coefficients of results in case LFG collection rate is reduced or increased by 50%

Scenario	S0	S1	S2.1	S2.2	S3.i.1	S3.i.2	S3.ss.1	S3.ss.2
GWP, kg CO_2-eq/share	-5E+8	-4E+8	-9E+8	-9E+8	-6E+8	-6E+8	-8E+8	-8E+8
EP, kg PO_4^{3-}-eq/share	2E+4	2E+4	3E+4	3E+4	2E+4	2E+4	3E+4	3E+4
AP, kg SO_2-eq/share	-8E+4	-7E+4	-1E+5	-1E+5	-1E+5	-1E+5	-1E+5	-1E+5
ADP_f, MJ/share	-4E+8	-4E+8	-8E+8	-8E+8	-6E+8	-6E+8	-8E+8	-8E+8

Furthermore, leachate generation is an uncertain parameter in the landfilling process. To test the sensitivity of this parameter, the results are obtained for values of leachate generation 50% higher than initially assumed one, which correspond to 0.3 ton of leachate per ton of MSW. The sensitivity coefficients for this parameter vary among scenarios as shown in Table 24, but the changes occur only in eutrophication potential. These variations correspond to the amount of MSW landfilled and reach up to 40 tons of PO_4^{3-}-eq per unit of leachate generation at the maximum.

Table 24. Sensitivity coefficients of results in case leachate generation is increased by 50%

Scenario	S0	S1	S2.1	S2.2	S3.i.1	S3.i.2	S3.ss.1	S3.ss.2
GWP, kg CO_2-eq /(kg_{leach}/kg_{msw})	0E+0	0E+0	0E+0	0E+0	0E+0	0E+0	0E+0	0E+0
EP, kg PO_4^{3-}-/(kg_{leach}/kg_{msw})	4E+4	3E+4	3E+4	3E+4	2E+4	2E+4	3E+4	3E+4
AP, kg SO_2-eq/(kg_{leach}/kg_{msw})	0E+0	0E+0	0E+0	0E+0	0E+0	0E+0	0E+0	0E+0
ADP_f, MJ/(kg_{leach}/kg_{msw})	0E+0	0E+0	0E+0	0E+0	0E+0	0E+0	0E+0	0E+0

To visualize how the results change with parameter variations, they are presented in Figure 17, Figure 18, Figure 19, and Figure 20 alongside with the initial results.

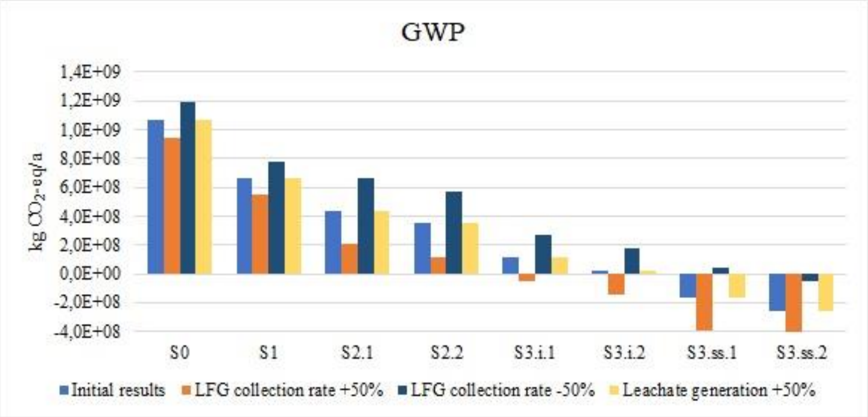

Figure 17. The results of sensitivity analysis for GWP

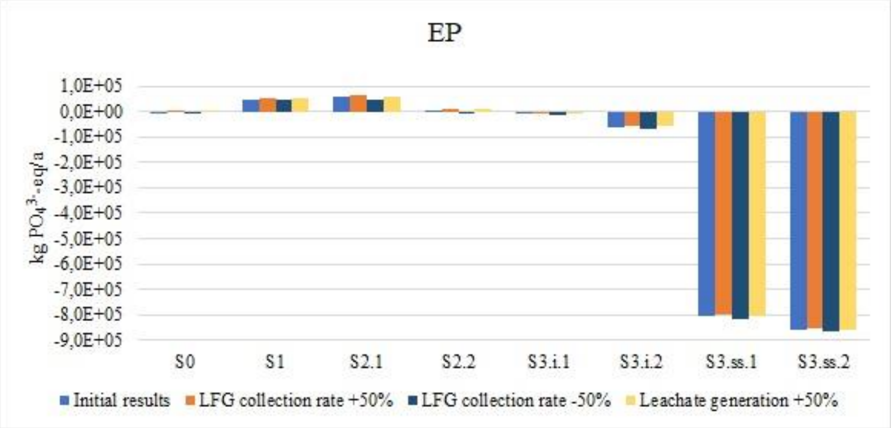

Figure 18. The results of sensitivity analysis for EP

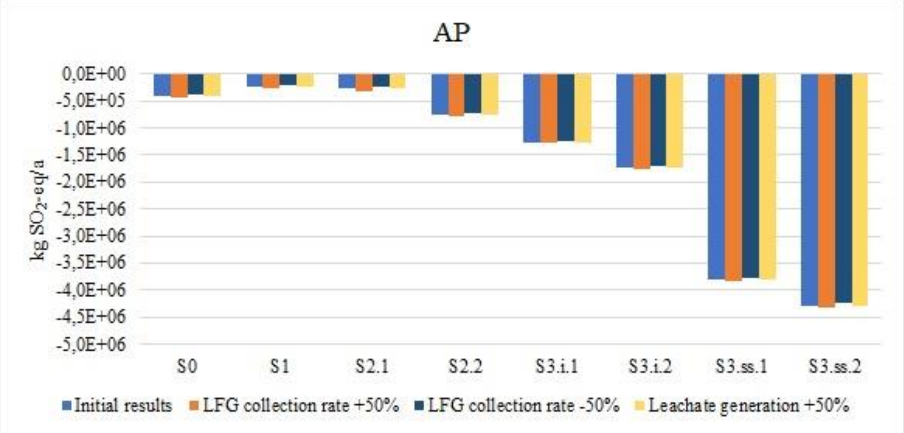

Figure 19. The results of sensitivity analysis for AP

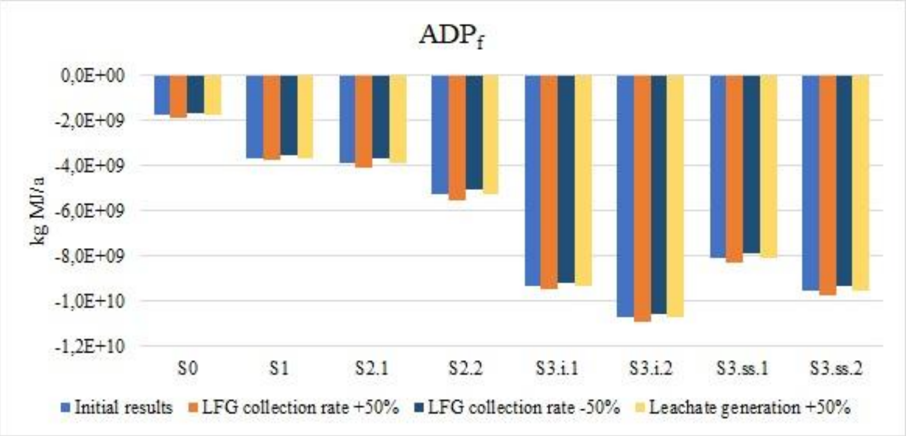

Figure 20. The results of sensitivity analysis for ADP (fossil fuels)

4.3 Scenario analysis

Scenario analysis can be necessary to test the robustness of the results when numerous assumptions are made to build the model. First, the response of the model to its very basic parameter – waste composition – is tested. The alternative data are considered for the Leningrad region only. From the baseline scenario onwards, the composition of MSW in the Leningrad region was based on data from Table 6 (a). However, one can notice that e.g. the organic waste share equal to 15% may be lower than it can be expected in the area. The alternative MSW composition from Table 6 (b) can be used to test the impact of these data on the overall performance of the system. Relative sensitivity of LCIA results regarding MSW composition is given in Table 25.

Table 25. Relative sensitivity of results in case MSW composition is changed for the Leningrad region

Scenario	S0	S1	S2.1	S2.2	S3.i.1	S3.i.2	S3.ss.1	S3.ss.2
GWP	0.23	0.33	0.35	0.43	0.81	3.95	-0.46	-0.28
EP	-104.44	0.22	0.23	1.94	-1.60	-0.15	0.13	0.13
AP	-0.20	-0.54	-0.43	-0.11	-0.10	-0.05	0.07	0.07
ADP$_f$	0.01	-0.01	0.00	0.02	-0.02	-0.01	0.02	0.02

The relative sensitivity of LCIA results to waste composition varies in a wide range. The increase of GWP roughly by 20-80% in most of the scenarios can be seen. This is due to higher shares of food, paper and cardboard waste in the alternative data (Table 6, b), which increased from 15% to 28% for food waste and from 8% to 20% for paper and cardboard.

For better visualization, GWP results are given in a diagram in Figure 21. Generally, the changes, which originate from MSW composition, can be multidirectional, as shares of recyclable materials also influence the results through the impact of recycling. Even though the direction of these changes is largely uncertain, the LCIA results can be rather sensitive to waste composition. It is important to mention that in this case the ranking of scenarios has not changed.

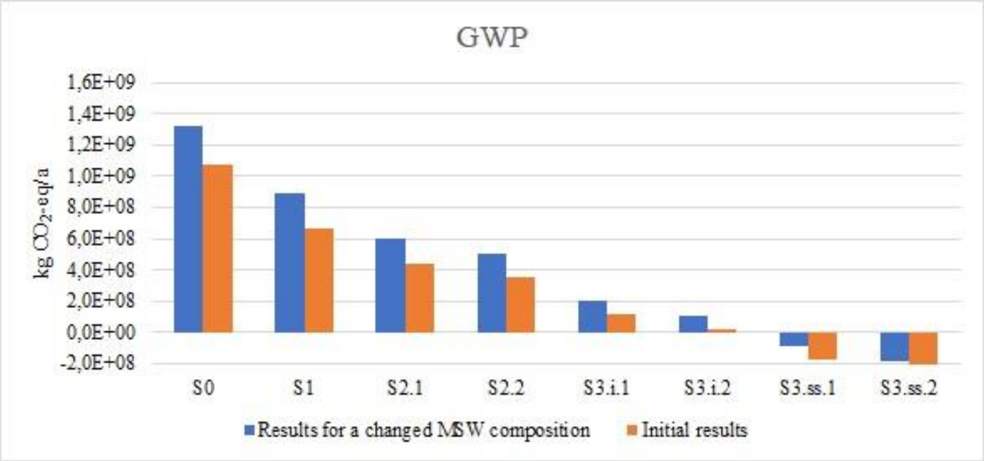

Figure 21. Scenario analysis results for GWP when MSW composition is changed

Next, the influence of the quality of source separation is assessed. In scenarios 3.ss.1, 3.ss.2, source separation of recyclable fractions was modelled using the EU average capture rates. However, capture rates can be expected to be lower during the first years of following separate collection practices. To assess the environmental impact of the MSW management system on the earlier stage of implementing source separation, capture rates of each fraction are assumed to be lower by 50%. According to this assumption, 8% of organic fraction, 8% of metals, 6% of plastics, 36% of paper and cardboard, and 22% of glass waste would be captured. The results calculated for such a case are presented in Table 26.

Table 26. Relative sensitivity of results in case capture rates are reduced by 50%

Scenario	S0	S1	S2.1	S2.2	S3.i.1	S3.i.2	S3.ss.1	S3.ss.2
GWP	0.00	0.08	0.11	0.19	0.17	1.68	-2.05	-1.40
EP	0.00	-0.76	-0.64	-4.93	4.14	0.34	-0.49	-0.48
AP	0.00	0.64	0.56	0.06	0.11	0.02	-0.42	-0.40
ADP_f	0.00	0.01	0.01	-0.05	0.00	-0.03	-0.26	-0.25

The changes in results in scenarios S1, S2, and S3.i originate from the reduction collected organic waste. The last scenario, which describes source separation of additional fractions, is predictably heavily dependent on capture rates. As seen in Table 23, GWP is affected the most. Moreover, the ranking of scenarios changed for GWP with the reduction of capture rates, leaving the incineration scenario (S3.i) as the most favorable one. This is depicted in Figure 22 below. Similarly, the ranking of scenarios changed for fossil resource depletion.

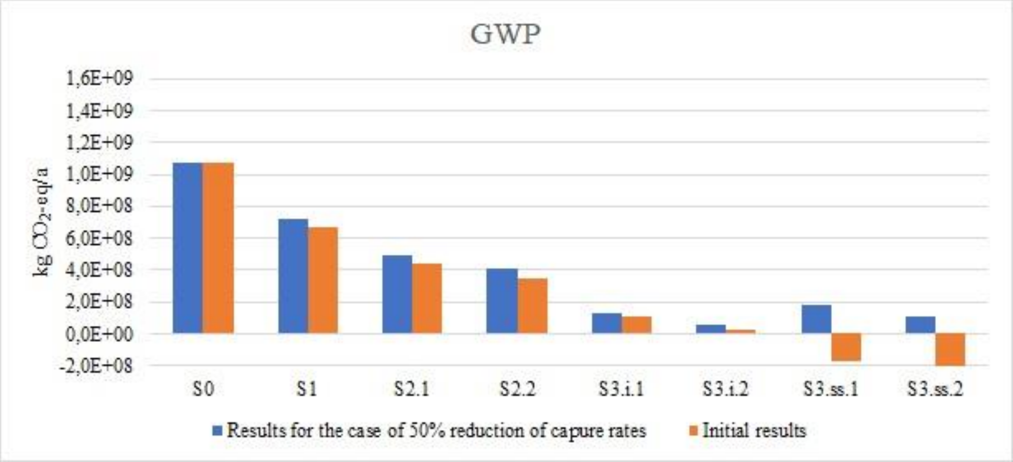

Figure 22. Scenario analysis results for GWP in case capture rates are reduced by 50%

Another assumption made in this LCA is the source of energy in substituted energy production. While electricity is supplied through the grid and therefore should be modelled as a grid mix, the heat production is local. The choice of energy source in this case, e.g. whether it is coal or natural gas, is more specific. In the model, some displacement of energy was modelled in all scenarios. It was assumed that substituted thermal energy is obtained from natural gas as the most common resource used in the studied area. Using another approach, it can be assumed that heat produced from MSW displaces coal-based heat, as a minor source that is currently being superseded. This assumption is tested using the GaBi unit process “RU: Process steam from hard coal 90% ts” as an avoided production. This change is applied to mixed MSW and RDF incineration, as well as biogas combustion.

The relative sensitivity calculated for this case is given in Table 27. The largest changes are observed in scenario S3.i, which is focused on MSW incineration as a treatment option. Acidification potential has the most drastic changes among impact categories (Figure 19): it is much larger when coal is used as a fuel. This is explained by the difference between natural gas and coal in nitrogen and especially sulfur content. Their acidifying emissions differ accordingly (EIA, 1999). Regarding AP, scenario S3.i becomes most beneficial for the studied system when coal-based thermal energy is displaced.

Table 27. Relative sensitivity of results in case coal is substituted as an energy source

Scenario	S0	S1	S2.1	S2.2	S3.i.1	S3.i.2	S3.ss.1	S3.ss.2
GWP	0.00	0.00	0.00	-0.05	-1.06	-6.32	-0.27	-0.10
EP	4.18	0.00	0.00	-0.47	1.74	0.27	-0.01	0.00
AP	0.03	-0.05	-0.04	0.72	2.83	2.36	-0.36	-0.19
ADP_f	0.00	0.00	0.00	-0.01	-0.02	-0.02	0.01	0.01

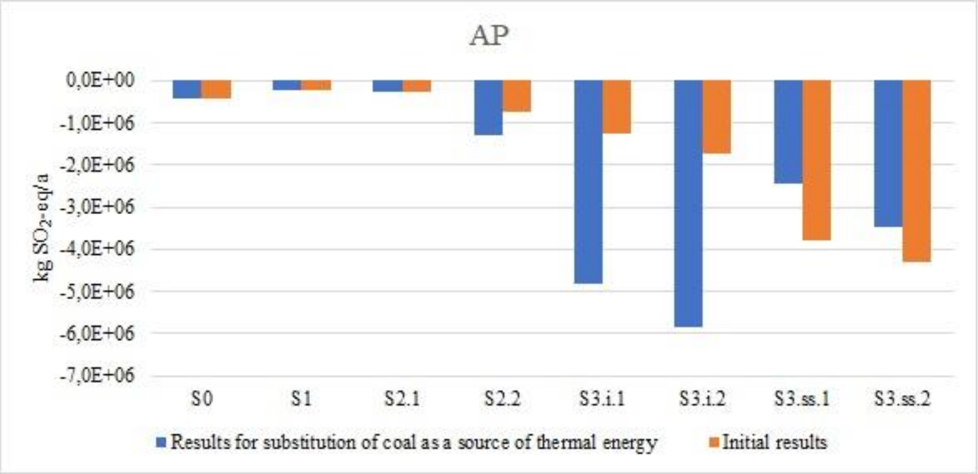

Figure 23. Scenario analysis results for AP in case coal-based thermal energy is substituted in the system

5 CONSLUSIONS

MSW management system in Saint Petersburg and the Leningrad region is a developing system. While landfilling is the most common method of waste treatment, some mixed waste is sorted, and the sorting practice tends to be expanded during the reformation of the waste sector. This and other proposed improvements are studied in this thesis via LCA for Saint Petersburg and the Leningrad region together.

The study faced many limitations and uncertainties in data and is based on secondary data. The TWMSs and governmental reports provided the basis of the knowledge on MSW management in the area. Further information was gathered from various sources, including design documentation for some facilities disclosed in public hearings, inspection reports on facilities published by governmental agencies, excursion materials from eco-activists. Very limited knowledge was obtained via communication with local companies working in the waste sector. The gaps in specific data were filled with literature data and assumptions. Also, due to the high uncertainty in transportation routes, this phase of waste handling was excluded from the study.

When tracking the improvement of the MSW management system step-by-step, one can see the overall reduction of its environmental burden. According to the results, the development of the system planned by 2024 can reduce GWP by 34% and ADP_f by 36%, while slightly intensifying eutrophication. Further doubling the amount of waste disposed of in landfills with LFG collection is estimated to cut GWP by 52% comparing to the baseline scenario; other impact categories do not change significantly with this advancement. Also, at this point, GWP could be reduced by 62% comparing to the baseline with the implementation of anaerobic treatment of organic waste instead of composting. EP and AP could decrease twofold. When 27% of MSW are sent to incineration, GWP can be expected to drop by 81% comparing to the scenario 0. A sharp reduction of fossil resource depletion also occurs, which compensates ADP_f of the whole MSW management system and gives negative ADP value. In the same way, acidification potential turns negative, and EP decreases significantly. Last but surely not least, source separation of metals, glass, plastics, paper, and cardboard contributes to the impact reduction. In scenarios 3.ss.1 and 3.ss.2, MSW management system in the studied region is estimated to be carbon negative and crucially reduce EP and AP. Roughly, it is a threefold reduction of AP and a sevenfold reduction of EP. Roughly, it is a threefold reduction of AP and a sevenfold reduction of EP. However, ADP of the system is significantly higher than in scenario S3.i.

Sensitivity analysis and scenario analysis were conducted to quantify possible variations of the results. As seen from the results, LFG collection rate and MSW composition can cause substantial variations of GWP. Also, if energy production from MSW displaces coal-based thermal energy production, a massive drop of acidification potential can be expected. In this case, the ranking of scenarios changes in AP impact category. The reduction of AP in scenarios with mixed MSW incineration (S3.i) exceeds the reduction reached by source separation (S3.ss) and becomes the largest among scenarios. Also, a critical influence on the results in terms of GWP was found in capture rates for separately collected recyclables. A double decrease of capture rates of each fraction, including biowaste, changes the ranking of scenarios and makes scenario S3.i the most beneficial for the system, while scenario S3.ss becomes the second favorable scenario for climate change mitigation.

Based on these results, the conclusion of the most effective waste handling practice should be specified. Source separation of MSW is estimated to provide the largest reduction of the environmental impact when capture rates of the average EU level are reached. However, this effect will take time to occur. As for the waste fraction, paper and cardboard waste recycling is associated with the most significant reduction of the environmental burden of the system. An important reason for this is the large share of paper and cardboard in MSW which is mostly sublect to landfill disposal in the current state of MSW management system. In all cases, the magnitude of the impact reduction is built upon MSW composition in the regions. Therefore, more accurate conclusions can be made if provided with updated information on waste composition.

Further research concerning other impact categories would be valuable. Particularly, the knowledge on ecotoxicity potential is important with regard to poorly developed separate collection of hazardous waste in Saint Petersburg and the Leningrad region. Being most concerning for Russian eco-activists and citizens, human toxicity potential would be an asset for this study. In this thesis, it was not estimated due to the lack of reliable data. Given less time constraint, even more extensive sensitivity analysis and scenario analysis can be done to deepen the knowledge on the variation of the result. As an example, possible effects of higher quality compost production can be estimated for separately collected organic waste.

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Amounts of processed MSW and fractions separated in Saint Petersburg

Facility	MSW sorted, t/a	Fractions separated	Reference
MPBO-2	169 000	Ferrous and non-ferrous metals, paper and cardboard, plastics, glass, screening reject	(MPBO-2, 2018b)
Staroobtyadcheskaya	100 000	Ferrous and non-ferrous metals, paper and cardboard, plastics, screening reject, RDF	(OOO “KOSMOS,” 2016)
Predportovaya	100 000		
OOO ”TEK”	56 302	Bulky waste, paper and cardboard, plastics	(Federal Service for Supervision of Consumer Rights Protection and Human Welfare, 2020; Waste Management Committee of the Leningrad Region, 2019a)
Sinergiya	41 386	Ferrous and non-ferrous metals, paper and cardboard, plastics, glass	

LCIA net results per kg of waste treated in a process

GWP net results per kg of waste treated in a process [kg CO_2-eq/(kg waste×a)]

Scenario	Landfilling	Steel recycling	Aluminum recycling	Plastic recycling	Glass recycling	Paper recycling	Composting	Anaerobic digestion	RDF incineration	MSW incineration
S0	0.40	-1.62	-10.41	-1.71	-0.42	-1.14	0.06		-0.71	-0.19
S1	0.35	-1.62	-10.41	-1.71	-0.42	-1.14	0.06		0.16	-0.19
S2.1	0.24	-1.62	-10.41	-1.71	-0.42	-1.14	0.06		0.16	-0.19
S2.2	0.24	-1.62	-10.41	-1.71	-0.42	-1.14	0.23	-0.20	0.16	-0.19
S3.i.1	0.18	-1.62	-10.41	-1.71	-0.42	-1.14	0.06		0.16	-0.02
S3.i.2	0.18	-1.62	-10.41	-1.71	-0.42	-1.14	0.23	-0.20	0.16	-0.02
S3.ss.1	0.19	-1.62	-10.41	-1.71	-0.42	-1.14	0.06		0.16	-0.20
S3.ss.2	0.19	-1.62	-10.41	-1.71	-0.42	-1.14	0.23	-0.20	0.16	-0.20

EP net results per kg of waste treated in a process [kg PO$_3^{4-}$-eq/(kg waste×a)]

Scenario	Landfilling	Steel recycling	Aluminum recycling	Plastic recycling	Glass recycling	Paper recycling	Composting	Anaerobic digestion	RDF incineration	MSW incineration
S0	0.000006	-0.000134	-0.004512	-0.000421	-0.001006	-0.003728	0.000392		-0.000280	-0.000074
S1	0.000007	-0.000134	-0.004512	-0.000421	-0.001006	-0.003728	0.000393		-0.000085	-0.000076
S2.1	0.000011	-0.000134	-0.004512	-0.000421	-0.001006	-0.003728	0.000393		-0.000085	-0.000076
S2.2	0.000011	-0.000134	-0.004512	-0.000421	-0.001006	-0.003728	0.001512	-0.000061	-0.000085	-0.000076
S3.i.1	0.000012	-0.000134	-0.004512	-0.000421	-0.001006	-0.003728	0.000393		-0.000085	-0.000067
S3.i.2	0.000012	-0.000134	-0.004512	-0.000421	-0.001006	-0.003728	0.001512	-0.000061	-0.000085	-0.000067
S3.ss.1	0.000012	-0.000134	-0.004512	-0.000421	-0.001006	-0.003728	0.000393		-0.000085	-0.000076
S3.ss.2	0.000012	-0.000134	-0.004512	-0.000421	-0.001006	-0.003728	0.001512	-0.000061	-0.000085	-0.000076

AP net results per kg of waste treated in a process [kg SO_2-eq/(kg waste×a)]

Scenario	Landfilling	Steel recycling	Aluminum recycling	Plastic recycling	Glass recycling	Paper recycling	Composting	Anaerobic digestion	RDF incineration	MSW incineration
S0	0.0001	-0.0026	-0.0704	-0.0026	-0.0059	-0.0120	0.0018		-0.0162	-0.0011
S1	0.0001	-0.0026	-0.0704	-0.0026	-0.0059	-0.0120	0.0018		-0.0049	-0.0012
S2.1	0.0001	-0.0026	-0.0704	-0.0026	-0.0059	-0.0120	0.0018		-0.0049	-0.0012
S2.2	0.0001	-0.0026	-0.0704	-0.0026	-0.0059	-0.0120	0.0068	-0.0008	-0.0049	-0.0012
S3.i.1	0.0001	-0.0026	-0.0704	-0.0026	-0.0059	-0.0120	0.0018		-0.0049	-0.0010
S3.i.2	0.0001	-0.0026	-0.0704	-0.0026	-0.0059	-0.0120	0.0068	-0.0008	-0.0049	-0.0010
S3.ss.1	0.0001	-0.0026	-0.0704	-0.0026	-0.0059	-0.0120	0.0018		-0.0049	-0.0012
S3.ss.2	0.0001	-0.0026	-0.0704	-0.0026	-0.0059	-0.0120	0.0068	-0.0008	-0.0049	-0.0012

ADP_f net results per kg of waste treated in a process [MJ/(kg waste×a)]

Scenario	Landfilling	Steel recycling	Aluminum recycling	Plastic recycling	Glass recycling	Paper recycling	Composting	Anaerobic digestion	RDF incineration	MSW incineration
S0	-0.08	-15.54	-97.11	-34.75	-2.00	-9.46	0.31		-18.24	-7.46
S1	-0.09	-15.54	-97.11	-34.75	-2.00	-9.46	0.20		-8.86	-7.55
S2.1	-0.19	-15.54	-97.11	-34.75	-2.00	-9.46	0.20		-8.86	-7.55
S2.2	-0.19	-15.54	-97.11	-34.75	-2.00	-9.46	0.27	-3.01	-8.86	-7.55
S3.i.1	-0.21	-15.54	-97.11	-34.75	-2.00	-9.46	0.20		-8.86	-6.38
S3.i.2	-0.21	-15.54	-97.11	-34.75	-2.00	-9.46	0.27	-3.01	-8.86	-6.38
S3.ss.1	-0.22	-15.54	-97.11	-34.75	-2.00	-9.46	0.20		-8.86	-7.91
S3.ss.2	-0.22	-15.54	-97.11	-34.75	-2.00	-9.46	0.27	-3.01	-8.86	-7.91