LAPPEENRANTA–LAHTI UNIVERSITY OF TECHNOLOGY LUT
School of Energy Systems
Department of Environmental Technology
Sustainability Science and Solutions
Master’s thesis 2020

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LIFE CYCLE ASSESSMENT OF THE EXISTING AND PROPOSED MUNICIPAL SOLID WASTE MANAGEMENT SYSTEMS IN MOSCOW

Examiners: Professor, D.Sc. (Tech.) Mika Horttanainen
D.Sc. (Tech.) Ivan Deviatkin

ABSTRACT

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Life cycle assessment of existing and proposed municipal solid waste management system in Moscow

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92 pages, 19 figures, 36 tables, 3 appendices

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Keywords: life cycle assessment, waste management, municipal solid waste

The study assesses the life cycle of the MSW management system in Moscow. As of 1 January 2019, new requirements in the waste management field were introduced at the legislative level, and by 2020 the MSW separate collection system should be implemented in all cities of Russia. Based on the territorial scheme of Moscow waste management approved in December 2019, scenarios for MSW management in 2020 and 2024 and alternative scenarios with separate collection and treatment of biowaste were simulated in GaBi software. Environmental impacts were assessed in three impact categories: global warming potential, acidification potential and eutrophication potential. The impact greatest reduction on climate change occurs in the Scenario 2.2 with 20% decrease of landfilling, increase in waste incineration share and recycling rates of secondary resources with additional implementation of anaerobic digestion for biowaste treatment. In this Scenario, greenhouse gas emissions could be reduced by 40%. The impact on acidification and eutrophication was reduced the most in Scenario 1, by 60-67%. The emission reduction potentials have been calculated for recyclable materials, the highest of which are metals and plastics, followed by paper, glass and biowaste.

ACKNOWLEDGEMENTS

I would like to express my gratitude to all structures of LUT University. I appreciate the opportunity to study here.

I would like to thank Ivan Deviatkin, my supervisor, for supporting the topic I have chosen, for mentoring me in the process of working on my thesis, and for providing me with a cheerful spirit. I would also like to thank Professor Mika Horttanainen for his trust and interest in my chosen topic.

My friends and colleagues, whom I met in Lappeenranta, thank you for spending this difficult and busy year with me, it will always be very special for me because of you. I would especially thank Tatiana Kaznacheevskaia, my dear flatmate, I will never forget how you cooked soup and took care of me after I had the surgery, and at the same time you made me laugh, and we were afraid that my stitches would split. Anna Zaikova, my soul mate in environmental issues, thank you, I will be always interested to hear your opinion on professional or any other topic. I also had a lot of support thousands of kilometers away from me, my fiancé and at the same time my friend Vladimir, I really appreciate it.

Thank you all for inspiring me every day and making this work possible.

In Lappeenranta 28th September 2020

Natalia Vinitskaia

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LIST OF SYMBOLS

m	mass	[kg]
M	molar mass	[kg/mol]
n	amount of substance	[mol]
T	temperature	[ºC]

Abbreviations

AP	Acidification Potential
BAT	Best Available Techniques
EP	Eutrophication Potential
GWP	Global Warming Potential
HDPE	High Density Polyethylene
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LFG	Landfill Gas
MBT	Mechanical-Biological Treatment
MSW	Municipal Solid Waste
MSWI	Municipal Solid Waste Incineration
PET	Polyethylene Terephthalate
RO	Regional Operator
SC	State Contract
SCW	Separately Collected Waste
SS	Sorting Station
TS	Transfer Station

Abbreviations from the Russian language

Abbreviation	Transliteration from Russian	Translation
BDO	Bank Dannyih ob Othodah	Waste Data Bank

FKKO	Federalnyiy Klassifikatsionnyiy Katalog Othodov	Federal Waste Classification Catalogue
KPO	Kompleks po Pererabotke Othodov	Waste Processing Complexes
MSZ	Musoroszhigatelnyiy Zavod	Municipal Solid Waste Incineration Plant
REO	Rossiyskiy Ekologicheskiy Operator	Russian Environmental Operator

1 INTRODUCTION

Moscow, being the capital of the Russian Federation, is one of the most populous cities in Europe. According to the Russian State Statistics Service (Rosstat), as of January 1, 2020, the population in Moscow exceeded 12.7 million people and will continue to grow. The total area of the city is 2570 km^2. The average population density is 5 000 people/km^2, but within the Moscow Ring Road it varies from 5 to 25 thousand people per square kilometer. For comparison, in New York, the density is about 10 500 people/km^2, and in Europe the highest level is in Paris - about 21 000 people/km^2. In this situation, the organization of procedures for the management of municipal solid waste (MSW) is a complex problem, the results of the solution of which depend on both the overall environment and health of the population, as well as economic parameters, and the development of the secondary material resources market.

According to the Territorial Scheme of Moscow Waste Management for 2020 (Official website of the mayor of Moscow, 2019), 8.1 million tons of MSW will be generated. Converted on per capita, that is about 640 kg/person. If taking into account that on average 420 kg of waste per capita is produced in Russia per year (Shamova and Myslyakova, 2019), the total volume of MSW generation in the country is about 70 million tons per year, and Moscow generates about 11% of the total volume of it. The difference between Moscow's relative waste generation rate and the average one is 1.5 times higher and this can be explained, firstly, by a higher standard of living and ability to purchase. Secondly, a large number of people working in the city live in the Moscow Region, which means that waste generated by them during the working day is also part of the total mass of MSW generation.

The Russian experience with MSW management is based on landfill disposal. Thus, in 2018, according to the state report "On the state and protection of the environment of the Russian Federation in 2018", the share of municipal solid waste transported to landfills was 87% of the total amount of MSW. About 2.2% of the total amount of MSW was transported for waste hazard reduction, including waste incineration plants, in 2018 (Ministry of Natural Resources and Environment of the Russian Federation, 2018).

Landfilling is considered to be the most unfavorable method of waste management, as it causes a number of negative environmental impacts. These effects may include soil and air pollution, and if the facility is designed incorrectly, can also lead to contamination of groundwater and surface water, occupation of large areas and greenhouse gas emissions. As for the latter, the impact is quite significant; for 2017 in Russia, the largest contribution to total greenhouse gas emissions in the "Waste" sector was made by CH_4 (methane) emissions from solid waste disposal - 73% (Ministry of Natural Resources and Environment of the Russian Federation, 2018). Such high volumes of methane formation at the landfills are caused by high percentage of organic matter in MSW and anaerobic processes of its decomposition.

Developed countries are trying to minimize the amount of waste sent to landfills. This strategy is enshrined as a waste hierarchy in EU Directive 2008/98. In the European Union, the share of landfilled MSW was on average 23% in 2018, and in the leading countries even less, e.g. in Finland only 0.9% of MSW (Statistics Finland, 2019) is sent to landfills, in Austria the percentage of landfills does not exceed 3% (European Parliament, 2018).

Currently, the policy of solid municipal waste management in Russia is changing significantly, new principles and rules are adopted, and targets are set for the development of the waste treatment sector. These changes are so fundamental that they are called the "Garbage Reform" in the mass media (Shamova and Myslyakova, 2019).

A fundamental step in the formation of a new waste treatment industry was the list of president's instructions and decisions on waste management regulation published in November 2017 (Russian President’s official website, 2017). The actual emergence of a new industry can be linked to the introduction by the Government of the Russian Federation in January 2018 of the "Strategy of industrial development for processing, utilization and hazard reduction of production and consumption waste until 2030" (ConsultantPlus, 2018a). In December, 2018 in the national project "Ecology" has been included as the individual Federal project "Complex system of the municipal solid waste management" and tasks till 2024 where introduction of territorial schemes in all 85 regions of the Russian Federation was included (ConsultantPlus, 2018b).

One of the most important goals today is to adapt successful global waste management practices to the conditions of the country and their implementation. Moreover, in decision-making it is necessary to systematically assess the most optimal system in these conditions. For example, in many countries, quite a high percentage of waste sent to incineration plants with electricity and heat generation, so these plants, in addition to MSW disposal, replace thermal power plants.

The life cycle assessment (LCA) approach is widely used in European and American countries and is based on systematic and comprehensive research. LCA can be used to assess the potential environmental impacts of the applied waste management system as well as to account for secondary material resources flows to other sectors of the economy. In this case, the LCA includes only the end-of-life phase of the product, i.e. the waste generation phase, and considers alternative treatment and disposal scenarios for this waste (Bakas et al., 2017).

LCA belongs to environmental management procedures and is standardized in the ISO 14000 series of international standards, which have been introduced and are currently in force in Russia. However, there are very few works focused on LCA of waste management systems in the Russian Federation. These are mainly the works of Tulohonova A. V. and Ulanova O. V. for the city of Irkutsk (2013), J. Kaazke from the Technical Institute of Berlin for Khanty-Mansiysk and Surgut (2013), and Vaysmann Y. I. et al. for Perm.

The purpose of this work is to assess and compare the environmental impact of the existing and alternative MSW management systems in Moscow using the LCA method. Baseline scenario and prospective scenarios based on waste management targets in Moscow will be assessed and proposals to reduce the negative impact on the environment will be developed.

Tasks to be performed in the work:

1. Assess the environmental impact of the existing MSW management system on the environment.
2. Assess the change of impact on the environment from planned changes in MSW management system for 2024 according to the territorial scheme of Moscow.

3. Reveal the fractions of municipal solid waste that have the greatest contribution to the existing negative influence on environment.
4. Identify the processes that have the greatest impact on the environment.
5. Assess the waste fractions with the highest potential to reduce the negative impact on the environment.

Based on the obtained results, it is possible to conclude what further actions in the waste management system of the city of Moscow will reduce the negative impact on the environment and will lead to a more rational resource allocation in different economic sectors.

The results of the life cycle assessment are presented in accordance with the standardized structure of the LCA.

2 MUNICIPAL SOLID WASTE MANAGEMENT IN THE RUSSIAN FEDERATION

2.1 Legislative framework

In the Russian Federation, one of the main laws reflecting the directions of state policy in the field of environmental preservation is the Federal Law "On Environmental Protection" dated January 10, 2002 No. 7-FZ (ConsultantPlus, 2002). It describes the principles of preserving a favorable environment, biological diversity and natural resources in order to meet the needs of present and future generations, address social and economic issues, and ensure environmental security. It also lists requirements for environmental protection in the management of production and consumption wastes.

The basic document regulating activity on waste management is the Federal law dated 24.06.1998 No. 89-FZ "On production and consumption waste" (ConsultantPlus, 1998). In it the basic principles of state policy in the above-mentioned field are formulated, including protection of human health, maintenance or recovery of a favorable condition of the environment, regulation of ecological and economic interests of a society for the purpose of providing sustainable development, application of the best available techniques (BAT) to reduce quantity of waste and their involvement in economic circulation, and also the international cooperation of Russia in the field of waste management. This document as a result of reforms in the waste management system has undergone changes with the amendments. The main documents that have made changes and currently regulate waste management are shown in Figure 1.

	Federal law **No. 7-FZ** "On Environmental Protection" (2002)	Main document on environmental protection in Russia.
	Federal law **No. 89-FZ** "On production and consumption waste" (1998)	Main document regulating waste management in Russia.
2014	Federal law **No. 458-FZ** "On Amendments to the Federal law No. 89-FZ"	The document introduces updated waste management terminology and new regulations. Introduces the concept of extended producer responsibility, regional operator and new economic incentive instruments.
2016	Government Resolution of the Russian Federation **No. 197** "On approval of requirements to the composition and content of territorial schemes of waste management, including municipal solid waste"	The document introduces requirements for territorial schemes of waste management.
	Government Resolution of the Russian Federation **No. 269** "On determining the standards for collection of municipal solid"	The document describes the method of calculation of MSW value (standard) at residential accumulation sites.
2017	Government Resolution of the Russian Federation **No. 1156** "On MSW management and amendment to the Government Resolution of the Russian Federation from 25.08.2008 No. 641"	The document describes MSW management regulations and requirements for waste transportation by a regional operator.
2018	Russian Government Executive Order **No. 1589-r** "The list of types of production and consumption waste, which include useful components, the landfilling of which is prohibited"	The document lists the types of waste that are forbidden for landfilling.
	Russian Government Executive Order **No. 84-r** "Strategy of industrial development for processing, utilization and hazard reduction of production and consumption waste until 2030"	The document defines the goals and methods of formation and development of the industry of processing, utilization and hazard reduction of waste.
	Government Resolution of the Russian Federation **No. 1039** "On approval of the Rules for arrangement of sites for collection of MSW and maintenance of their register"	The document contains rules for setting MSW collection sites and maintaining a registry of these sites.
	Federal law **No. 483-FZ** "On Amendments to section 29.1 of the Federal law No. 89-FZ"	The document introduces a postponement of providing MSW management regulations until 2022 for Moscow, St. Petersburg and Sevastopol.
	Introduction of the national project "Ecology"	The document defines the plan until 2024 of implementation of the new MSW management system and liquidation of unauthorized dumps.
2019	Federal law **No. 225-FZ** "On amendments to the Federal law No. 89-FZ" and the Federal Law "On the State Atomic Energy Corporation Rosatom"	The document introduces the Russian environmental operator of waste management.

Figure 1 – Main documents regulating waste management and making changes to the old legislation

No. 89-FZ sets priorities for state policy in waste management, and from 2014 they look as follows in descending order of priority:

- maximization of use efficiency of raw materials and inputs;
- prevention of waste generation;
- reduction of waste generation and reduction of the hazard category of waste in the sources of waste generation;
- waste processing;
- waste utilization;
- waste hazard reduction;
- waste disposal (storage and landfilling).

Depending on the extent of potential impact on the environment, all wastes are divided into 5 hazard classes according to criteria established by the Federal Executive Agency. These hazard classes are also specified in Federal Law No. 89-FZ and are grouped as follows:

- Class I – extremely hazardous waste;
- Class II – high-hazard waste;
- Class III – moderately hazardous waste;
- Class IV – low-hazard waste;
- Class V – almost non-hazardous waste.

All types of waste generated in the context of industrial or residential activities should be classified in a certain hazard class. It is determined based on the chemical and/or component composition of the waste and is established:

- based on the Federal Waste Classification Catalogue (Federalnyiy Klassifikatsionnyiy Katalog Othodov, FKKO) and the Waste Data Bank (Bank Dannyih ob Othodah, BDO) formed by the Federal Service for Supervision of Natural Resources (Rosprirodnadzor);
- in case of absence of waste type in FKKO and BDO, on the basis of criteria for classification wastes to I - V hazard classes, approved by the Ministry of Natural Resources and Ecology of the Russian Federation (ConsultantPlus, 2015)

FKKO classifies waste by origin, aggregate state and potential hazard to the environment. For MSW, the term "municipal solid waste" is used in FKKO and the section code corresponds to 7 31 000 00 00 0.

Legal entities and individual entrepreneurs who generate wastes of hazard classes I - IV are obligated to prepare a passport for all types of wastes and report on their management methods. Since different hazard classes of waste require different actions and the degree of responsibility for their treatment, the work on collection, transportation, processing, waste hazard reduction, material recovery, disposal of waste should be licensed in accordance with the Federal Law dated 4th of May 2011 No. 99-FZ "On licensing certain types of activities".

Basically, MSW belongs to hazard class IV or V. The handling of waste class V does not require licensing and development of waste passports. However, there is not much waste in hazard class V. This includes, for example, bulky waste and garden waste. As for the separately collected recyclables from MSW, the FKKO code is currently under development (ClassInform, 2020).

Since January 1, 2019 amendments to the Federal Law "On Production and Consumption Waste" are in force. Subsection 1 of Section 8 defines the scope of activities of local authorities in the field of municipal solid waste management. It includes:

- Creation and maintenance of cleanliness and functioning of places, which are allocated for collection of MSW. Exceptions are cases when this responsibility is assigned to other entities.
- Independent placement of dedicated sites for MSW collection.

According to subsection 13 of the Government Resolution of the Russian Federation from 12.11.2016 No. 1156 "On MSW management and amendment to the Government Resolution of the Russian Federation from 25.08.2008 No. 641" all regional operators are fully responsible for the MSW management from the moment they have loaded them into the waste truck and directed them to the places of their treatment and disposal (ConsultantPlus, 2018c).

In 2018, the Law No. 483-FZ "On Amendments to section 29.1 of the Federal Law "On Production and Consumption Wastes" was adopted. According to it, cities of federal value are given the right till the 1st of January, 2022 not to apply provisions of the federal legislation on treatment of a waste in territory of the subject of the Russian Federation by regional operators. Thus, Moscow and Saint-Petersburg, as well as Sevastopol have the right to use deferred until 2022 (Sumbaeva, 2020).

In 2018 in fact, a new industry was formed with the Russian Government's approval of the "Strategy of industrial development for processing, utilization and hazard reduction of production and consumption waste until 2030". The adoption of the strategy is a step towards the development of domestic recycling of waste and its involvement in economic turnover.

It defines the goals and objectives for the long-term perspective, priorities and stages of implementation of state policy in the formation and development of the industry for the processing, recycling and disposal of industrial and consumer waste, including municipal solid waste.

The strategy states that at the moment the overwhelming number of secondary materials is excluded from economic turnover. At the same time, the country has a significant number of potential waste recycling companies, underutilized waste recycling facilities, established and patented the best available domestic waste management technologies. The reason for this situation is to some extent the cheapness of waste landfilling. It is supplemented by the problem of existence of a large number of unauthorized landfills, in the detection and prevention of the formation of which should operate state control and supervision measures that are insufficient at the moment.

The strategy emphasizes the need to apply international experience in waste and secondary resource management in order to develop the industry. This experience is based on building a closed-loop economy, applying the 3R (reduce, reuse, recycle) principle, i.e. waste prevention, reuse of materials, recycling of waste resources.

Federal Law No. 89-FZ prohibits the landfilling of wastes that contain useful components. The list of such types of waste is approved by the Russian Government Order No. 1589-r dated 25.07.2017. As of 1 January 2018, 67 items on the list, such as mercury and fluorescent lamps, scrap of ferrous and non-ferrous metals, should not be landfilled. As of January 1, 2019, the ban on landfill applies to items 68 - 109 of the list, i.e. uncontaminated waste paper and cardboard, car tires, container glass, polyethylene waste, etc. The last section of the list 110 - 182 comes into force from 2021 and contains such types of waste as computer equipment, mobile phones, electrical cell, batteries and different kinds of household appliances (ConsultantPlus, 2017).

Territorial schemes for all 85 subjects of the Russian Federation should be developed on the basis of the Decree of the Government of the Russian Federation № 197 "On approval of requirements to the composition and content of territorial schemes of waste management, including municipal solid waste" dated 16.03.2016. Territorial scheme of waste management is a description of the system of collection, transportation, processing, utilization, waste hazard reduction and landfilling of waste, as well as zoning of the territory of the subject of the Russian Federation, where the activity is conducted, typically for a certain period of 10 years. It allows to make a quantitative assessment of existing volumes of generation, to determine the flow of solid municipal wastes, to make an inventory of authorized and illegal places of their disposal. The territorial scheme contains:

- data on the location of sources of waste generation;
- data on the amount of waste generated by waste types and hazard classes;
- data on waste treatment and disposal targets, disaggregated by year;
- data on the location of waste collection sites;
- data on the location of waste processing, treatment and waste hazard reduction facilities;
- data on location of waste disposal facilities included in the State Register of Waste Disposal Facilities;
- balance of quantitative characteristics of waste generation, processing, treatment, waste hazard reduction and landfilling;
- waste flow scheme, including MSW;
- estimation of the volume of relevant capital investments into construction, reconstruction, decommissioning of waste treatment, waste hazard reduction;
- and disposal facilities;
- forecasted values of charges for treatment of waste;
- information on areas of operation of regional operators;
- electronic model of territorial scheme of waste management.

As of January 1, 2019, not all subjects of the Russian Federation had developed and put into operation territorial schemes as planned, but only about 70 out of 85.

According to No. 89-FZ "On Production and Consumption Wastes", the activities on collection, transportation, processing, utilization, as well as waste hazard reduction and landfilling are taken over by the regional operator. Regional operator - legal entity with which the owner of waste enters into contract for the provision of services for waste management, if the place of collection of generated MSW is in the area of operation of the regional operator.

It is necessary to note that for today the area of responsibility of the regional operator does not include all MSW formed in the territory of the subject. According to Section 9, No. 458-FZ "On Amendments to the Federal Law "On Production and Consumption Waste" of 29.12.2014, if before January 1, 2016 in the subject of the Russian Federation state contracts are signed for the provision of services for the handling of MSW for a period of more than 10 years, before the expiration of these state contracts the regional operator does not provide the service to handle of MSW.

In summer 2019 the Federal Law № 225-FZ "On Amendments to the Federal Law" On Production and Consumption Wastes" and the Federal Law "On the State Atomic Energy Corporation "Rosatom" from 26.07.2019 was adopted, which introduces a new player in the field of waste management - the Russian Environmental Operator (REO) (ConsultantPlus, 2019). REO is a public-law company established in accordance with the Decree of the President of the Russian Federation for the purpose of forming an integrated system of waste management, ensuring preventing the harmful impact on human health and the environment, involving such waste in the economic turnover as feedstock and energy source, as well as for resource saving purposes. The Ministry of Natural Resources and Environment of the Russian Federation is the founder of the REO. Now, before coming into force, draft territorial schemes should be sent for consideration of REO for compliance with the requirements of legislation and economic feasibility of decisions.

2.2 Terminology

First of all, it is necessary to clarify what exactly the terminology for MSW management that is used in the study. The main terms are contained in No. 89-FZ and are described below.

Municipal solid waste (MSW) means waste generated in residential premises in the process of consumption by individuals, as well as goods that have lost their consumer properties in the process of their use by individuals in residential premises to meet personal and domestic needs. MSW also includes wastes generated by legal entities, individual entrepreneurs and similar in composition to wastes generated in residential premises in the process of consumption by individuals.

In accordance with the FKKO, the MSW includes the section number 7 30 000 00 00 0 - Municipal waste, as well as similar waste at the production site and in the provision of services to the public and 7 40 000 00 00 0 - Waste from the processing, utilization, waste hazard reduction, disposal of waste, which includes sorting residues of solid municipal waste. The first section includes:

- Municipal solid waste;
- Consumption waste in the workplace, similar to municipal waste;
- Waste in the provision of transport services to the public;
- Wastes in the provision of wholesale and retail trade services related to MSW;
- Waste in the provision of hotel and catering services, social services to the public;
- Wastes in the provision of education, art, entertainment, recreation and sports services related to MSW;
- Waste in the provision of other types of services to the population.

Waste management includes activities related to the collection, transportation, processing, utilization, waste hazard reduction and disposal of waste. Further definitions of the basic kinds of activity on waste management from the Federal law "On production and consumption waste" are presented:

- Processing of waste means preliminary preparation of a waste for the further utilization, including their sorting, disassembly, clearing;
- Waste hazard reduction of waste means reduction of weight of waste, change of their structure, physical and chemical properties (including incineration, except for incineration with energy recovery, and (or) disinfection on specialized units) for reduction of negative impact of a waste on human health and environment;
- Waste utilization means use of waste for production of goods (products), performance of works, provision of services, including reuse of waste, recycling, material recovery and energy recovery as a result of use of MSW as a renewable energy source after extraction of useful components from them;

- Waste disposal means storage and landfilling of waste;
- Waste storage means storage of wastes in specialized facilities for more than eleven months for the purpose of utilization, waste hazard reduction and landfilling;
- Waste landfilling means isolation of waste which is not subject to further utilization in special storage facilities in order to prevent infiltration of harmful substances into the environment.

2.3 MSW management in Moscow

Although the separate collection system has already started to be implemented, the most of municipal solid waste in cities is collected in a predominantly mixed manner, i.e., waste is not sorted at the source of generation and it is collected in a single bin. With a mixed collection system, the recovery efficiency of secondary resources (paper, cardboard, glass, metal, plastic bottles, polymer waste) has been significantly reduced, as their quality is deteriorated by soaking and contamination, and metal waste (fine-fraction) is blended into the total mass. The use of a mixed waste collection system reduces the extraction of recyclables, increases the loading of landfills and the associated harmful emissions.

To implement separate collection and recycling of waste, it is necessary to know the composition of the collected waste. Composition means the content of individual components of waste, which are expressed as a percentage of their total mass. MSW composition varies depending on the level of development of regions and the country in general. Countries with different levels of development face different challenges regarding municipal solid waste. While in underdeveloped countries the main issue is sanitation (a large amount of organic waste contributes to the spread of dangerous diseases), developed countries face more complex issues: loss of natural resources, chemical pollution, etc. In the so-called transitional countries (to which, according to this classification, Russia belongs) the problem of MSW can be considered as a combination of both problems.

It should be noted that no systematic research has been conducted on the composition of MSW in Russia. The only source of statistical information is micro-research conducted by research groups, organizations, operators and associations in individual regions at different times. However, their conclusions differ significantly from each other.

2.3.1 MSW composition

Mixed MSW is a polycomponent system with a complex chemical composition, so it can be dangerous for human health. The presence of organic fraction in MSW (food, plants, etc.) as well as the content of hazardous waste class 1 and 2 ("hazardous waste") make it possible for various diseases to occur due to toxic components entering the soil and groundwater. The problem of recycling and disposal of hazardous waste generated in the municipal sector has a special role. Hazardous wastes are those which, due to their content of toxic substances such as heavy metals and organochlorine compounds, should not be disposed of in conventional MSW landfills.

The following factors that affect the composition of MSW are outlined:

- time (period, season, day of week);
- territory (climate, transport accessibility);
- socio-economic factors (source of waste, population structure, level of improvement, availability of tourist centers, protection areas, development of the market for recyclable materials);
- sanitary-technical factors (MSW collection system (mixed or separate), type and size of the bin, frequency of emptying, degree of development of sanitary cleaning of the locality).

The "Strategy of industrial development for processing, utilization and hazard reduction of production and consumption waste until 2030" provides the ranges of MSW distribution to certain waste types. These data are used for further application in the work, and are summarized in Table 1. As a comparison, the table reflects the average composition of waste in Finland (KIVO.fi, 2017), Germany (Andreasi Bassi et al., 2017) and the USA (US EPA, 2017).

Table 1 – Average MSW composition in Russia (ConsultantPlus, 2018a) and other countries

Waste type	Share of waste in MSW in Russia, %	Share of waste in MSW in Finland, %	Share of waste in MSW in Germany, %	Share of waste in MSW in the US, %
Paper and cardboard	39.5	16.5	21.5	25.0
Biowaste	31.0	32.8	30.9	27.1
Plastics	6.0	16.7	15.6	13.2
Glass	5.0	2.4	6.7	4.2
Textile	4.5	4.7	2.6	6.3
Waste wood	3.0	1.5	3.2	6.7
Ferrous metals	3.0	-	-	-
Leather and rubber	2.5	1.6	-	3.4
Stones	2.5	-	-	-
Non-Ferrous metals	1.5	-	-	-
Bones	1.5	-	-	-
* Metals	-	2.3	6.1	9.4
* Electrical equipment and batteries	-	1.1	1.5	-
* Dangerous chemicals	-	0.4	0.2	-
* Miscellaneous wastes	-	18.4	11.6	3.4

* – type of waste different from the Russian classification

All fractions of municipal solid waste can be conditionally divided into three groups depending on the direction (priority) of treatment:

- fractions with biological potential and biodegradable (food waste, garden waste, paper and cardboard, sifting);
- fractions with energy potential (paper and cardboard, cardboard, plastic, wood, textiles);
- fractions with recyclable potential (metal, glass, rubber, paper and cardboard, plastic).

Table 1 indicates that MSW has a very high percentage of paper and cardboard in Russia and a relatively small percentage of plastic compared to other countries. This can be explained by the fact that the data are average for Russia, including rural areas and can also be based on old data.

2.4 Territorial scheme of MSW management in Moscow

According to Rosstat, the permanent population in Moscow currently exceeds 12.6 million people. The city area is 2 570 km², and the territory is divided into 12 administrative districts: Central, Northern, North-Eastern, Eastern, South-Eastern, Southern, South-Western, Western, North-Western, Zelenograd, Troitsk and Novomoskovsk.

According to the territorial scheme made in 2019 (Official website of the mayor of Moscow, 2019), 8.1 million tons of MSW were estimated to be formed in Moscow in 2020 across all administrative districts. Information on the amount of generated municipal solid waste and the trends in its generation is needed in order to assess current and future needs in budgeting systems, maintenance, processing, utilization and disposal.

As mentioned earlier, from January 1, 2019 regional operators for MSW management should have been selected on a competitive basis, but state contracts signed before 01.01.2016 for more than 10 years are not terminated and continue to be in force (Part 9 of Section 23 of the Federal Law from 29.12.2014 N 458-FZ). Thus, on the territory of Moscow waste management activities are carried out by regional operators (RO) and contractors under state contracts (SC). According to the strategic plans, from January 1st, 2020, the first stage of implementation of separate waste collection system in Moscow should be realized, and RO and contractors under SC responsible for waste management should also be defined.

2.4.1 Collection of MSW

Container sites for waste collection may be located on the adjacent territories, in other words, in front of multi-apartment buildings. If the houses are private, for example in the more rural areas, then one container site is chosen for a certain number of houses, so it is not on the adjacent territory. MSW is collected in Moscow in the following categories of locations:

- Container sites for municipal solid waste;
- Bunker sites for bulky waste;

- Sites for withdrawable bins;
- Sites for separate waste collection.

In 85% of cases, 0.8 and 1.1 m^3 bins are used for waste collection. According to the territorial scheme for 2019, the number of container sites in adjacent territories is 18 thousand, 95% of which are equipped for separate waste collection, and by 2020 all the sites will be equipped. The situation is different for collection sites that is not on the adjacent territories. The total number of such sites is about 19.2 thousand, but only 33% of them have bins for separately collected waste (SCW).

On sites equipped for SCW there is a two-bin collection system. Its principle is to separate contaminated waste from waste containing useful components that can be recycled and the organic fraction from mixed waste is not separated. For convenience, two types of bins are coloured differently, Figure 2. The blue bin is for sorted waste: paper, cardboard, metal, plastic, glass whereas the grey bin is for mixed waste. Hazardous waste, bulbs, thermometers, batteries, etc. is planned to be collected in specialized public places and for them orange bins will be installed, but such waste does not belong to MSW.

Figure 2 – Two-bin waste collection system

In the future, both mixed and separately collected MSW are subject to sorting, but secondary materials recovery from the separately collected waste can reach over 50%, while from mixed MSW the recovery limit is 25% (Official website of the mayor of Moscow, 2019).

2.4.2 Transportation of MSW

Transportation is carried out by vehicles, which must be equipped with GLONASS satellite tracking systems and GPS. Traditionally, transportation of MSW from the collection site to the sorting or transfer station (TS) is carried out by waste trucks with rear loading. They are equipped with a compression mechanism and are efficient for small volume operations at short distances. For the long-distance transportation of the waste that has been sorted or transferred, large-tonnage lorries equipped with a hook loading system "multilift" are used. The diagram of such a system is shown in Figure 3.

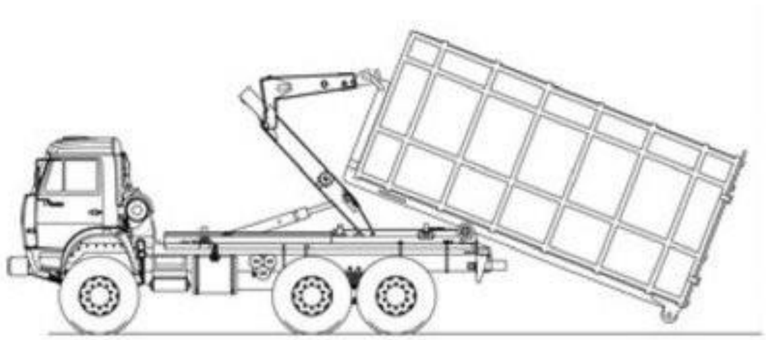

Figure 3 – The diagram of lorries with the "multilift" system

Due to the need to transport waste over long distances to the disposal site, Moscow is preparing to launch 4 waste transfer stations. Incoming MSW will be transferred and part of them will be sorted and then sent by rail to the disposal sites.

2.4.3 Processing of MSW

In addition to four TS in Moscow and the Moscow region there are 11 processing stations. At each such station there should be a checkpoint where incoming waste is weighed, cargo is registered and radiation control is performed. Radiation control of incoming MSW is carried out by a stationary radiation threshold alarm device.

The target for 2020 for the waste to be treated is only 27% of the total amount of MSW collected and should reach at least 60% by 2024. Processing can include the following activities: MSW manual or mechanical sorting, storage of sorted secondary materials, crushing of large-size waste, compacting MSW and residue after sorting, sending secondary materials to recyclers.

2.4.4 MSW incineration and disposal

MSW is mainly classified as hazard class IV and V and thermal hazard reduction usually refers to waste incineration. If MSW incineration plants (MSWI) produced energy and supplied it to the grid, in Russia this activity would relate to waste utilization along with recycling. But none of the incineration plants supply energy to the grid, so they are classified as thermal hazard reduction facilities. As of 2020, there are 2 waste incineration plants operating in Moscow, these are "EcoTechProm MSZ-3" (360 t/year capacity) and "Khartiya" MSZ-4 (250 t/year capacity) in Rudnevo (Musoroszhigatelnyiy Zavod, MSZ). By 2024, Moscow waste will be sent to an additional four MSWI plants in the Moscow region: "Voskresensk", "Noginsk", "Solnechnogorsk", "Naro-Fominsk" (350 t/year capacity each). The shares of MSW, according to the target values of thermal waste hazard reduction, is 3.8% and 17.6% for 2020 and 2024 respectively.

Analyzing the targets, it should be noticed that in 10 years, landfilling will still be the predominant way of municipal waste management. If in 2020 the share of MSW sent for disposal is 83.8%, in 2029 it is planned to decrease it to 64%. By 2020, disposal will be carried out at 11 so-called waste processing complexes (Kompleks po Pererabotke Othodov, KPO) in the Moscow region, landfill in the Kaluga region and presumably one landfill in the Vladimir region, for which there is no data in the territorial scheme at the moment. KPO refers to a landfill with a preliminary sorting line with a 20% recovery rate of secondary material resources from mixed waste.

The territorial scheme of MSW management in Moscow was published in December 2019, but contains a lot of inaccuracies and requires improvement. For example, in terms of target values, the share of waste processing in the total mass of MSW collected significantly increases, while the list of waste sorting facilities decreases over the years. This means that part of the necessary data is missing, which makes it difficult to understand the real situation. Also, detailed information is only available on incineration plants (only two of them) and waste sorting facilities, and data on disposal facilities and new incineration plants is not available. Moreover, the flow routes of sorted secondary resources are not mentioned in the document.

It is quite probable that the list of MSW treatment facilities will be corrected, as the document does not contain information on landfill sites in the Vladimir region due to the lack of an official decision regarding work with them. It was also planned to include EcoTechnoPark "Shies" in Arkhangelsk region in the list of Moscow MSW disposal sites, capable of receiving 500 thousand tons of MSW per year, but due to mass protests in 2018 the construction of the facility was suspended by court order, but its further fate is unclear (INTERFAX.RU, 2020).

The territorial scheme of waste management for the city of Moscow, which will be used in the study as the main source of data on the waste management system in this region, has a number of shortcomings. However, it is the only official resource on which it is decided to analyze the current situation. The absence of a unified database on the quantity and quality of waste, waste composition, and the amount of waste generated in the regions makes the work more complex and leads to results that are different from the actual ones. Gaining a real picture of waste management is also hampered by lost waste flows that are discharged to unauthorized dumps.

3 LIFE CYCLE ASSESSMENT METHOD

3.1 Concept of Life Cycle Assessment

Today, one of the most common environmental management tools worldwide is Life cycle assessment (LCA). It involves a systematic analysis of all stages of the life cycle of the products under study, from the extraction of raw materials for their production to the end-of-life stage after use. Instead of products, a service may be subjected to the study, including a service for waste management, from the stage of their generation to the final utilization of all fractions. The main purpose of LCA is to identify the environmental impacts throughout the life cycle of a product (or service) in use and compare it with alternative solutions that will reduce environmental impacts and improve product environmental efficiency. Social and economic aspects are not usually analyzed in the study.

LCA reports are used by decision makers in industrial, governmental or non-governmental organizations for strategic planning, priority setting, product or process design or redesign, as well as for marketing purposes (e.g. implementing an environmental labelling scheme, environmental statements or environmental declarations). The life cycle assessment method has a fixed structure and is conducted in accordance with the international standards ISO 14040 and ISO 14044. One of the characteristic requirements for research and reporting is that results should be accessible and transparent so that they can be easily repeated by someone else.

There are four compulsory stages in the implementation of LCA: 1. identification of goal and scope of the study; 2. inventory analysis; 3. impact assessment; 4. interpretation of the results.

The first stage establishes the goal of the study and describes the scope of the system in question depending on the purpose, extent of detail and width of the study. This stage also specifies the methods to be used in impact assessment and the assumptions used in the work.

The second stage, the Life Cycle Inventory analysis (LCI) stage, involves a description of all baseline data, input and output parameters of the system under review, including processes, resource flows, energy and emissions. The data collection process is iterative in nature due to the need to adjust the processes as they are detailed or new assumptions are introduced.

At the stage of Life Cycle Impact Assessment (LCIA), the potential environmental impacts of the system under study are analyzed. LCIA consists of three compulsory stages, namely the stage of selecting a characterization model and impact categories, the stage of classification and the stage of characterization. If necessary, the normalization, grouping and weighing stages can be added.

Classification is the process of classifying emissions into one or more impact categories. Characterization involves converting the results into reference units, with each impact category having its own units. For example, for the global warming potential, the reference units are [CO_2-equivalent]. This conversion is done by multiplying the result by a characterization factor. The results of the impact assessment describe potential environmental impacts without reference to impact, safety or risk thresholds.

At the interpretation stage, all conclusions obtained at previous stages are summarized and agreed upon, and recommendations appropriate to the purpose are made to the decision-makers. Thus, at this stage, the results of the whole life cycle assessment should be presented.

3.2 Types of impacts from waste management

With regard to the waste management system, according to Laurent et al. (2014) the most frequently reported impact categories are non-toxic impacts, which include climate change, ozone depletion, eutrophication and acidification. About 60% of the studies also include toxic impact categories in which toxic effects on humans or the environment are assessed. Almost half of the LCA studies of solid waste management assess non-renewable resource depletion and less often land use or water use categories. The impact on climate change arises from the formation of greenhouse gases through various processes related to waste management, transportation and disposal. A solution for climate change mitigation could be modelling an extended system, i.e. preventing emissions by recycling and substituting products from primary sources on the market. Climate benefits also occur from incineration of waste with electricity and/or heat generation if it substitutes fossil energy sources. Toxic emissions for ecosystems and humans are mainly related to incineration and landfilling of waste. Toxic emissions also have a time dimension, as they can be released very slowly and cause problems in the future.

Depending on the waste management methods, different environmental impacts may occur. Waste landfilling: If the leachate generated by water infiltration into the waste mass is not collected properly by the drainage system, the surrounding soil and groundwater can be contaminated with organic and inorganic (e.g., metals) pollutants. The gas produced by anaerobic degradation of organic substances contains methane, a strong greenhouse gas, and in the absence of a collection system, is released to the atmosphere. Incineration: emissions to air may affect local ecosystems. In addition to large amounts of CO_2, fly ash and hazardous halogen compounds can be carried by flue gases. Bottom ash contains significant concentrations of toxic heavy metals that can potentially be leached after deposition. Recycling: recycling activities are mainly related to energy consumption for waste and chemicals, but usually have less impact than the primary production of the same materials. Thus, the complexity and diversity of environmental issues arising from waste management requires an integrated approach such as LCA, which considers all potential environmental impacts (Klöpffer, 1997).

3.3 The software

Environmental processes are difficult to model because of their complexity and variability, and the LCA method often requires large amounts of data. To simplify the work with large volumes of information, different software is used. They also help structure the simulated scenario by visualizing process chains, presenting and analyzing the results. The software tool typically consists of a database and a modeling module. The data is processed and modeled on an interface.

Modeling consists mainly of connecting serial processes with material flows. Each process represents a stage in the life cycle of the object under study and is determined by its input and output data. The output data of the previous process form the input data for the next process. Simple process chains can be modeled into a single layer, but a hierarchical structure is required to handle more complex systems.

There is a large number of software products on the world market, both highly specialized in a particular sector of industry and multidisciplinary. Here are some of the programs most popular and applicable on the European market:

- SimaPro - Netherlands;
- GABi, UMBERTO - Germany;
- EASEWASTE - Denmark;
- Ecoinvent - Switzerland.

This study modeling is done in the GaBi software (Sphera, 2020). It is a tool for life cycle assessment and life cycle engineering. The program's database contains information from industry and various literature sources indicating time and geographical specialization. Using the database helps to reduce and simplify the time required to model secondary processes and resulting harmful emissions. For example, when modelling a glass recycling or production process in which quartz sand is an input resource, the impact of extracting and transporting that resource must be taken into account. In processes from the database, impacts during the life cycle of the resource are already taken into account.

This program also has the advantage that non-OECD students have access to a free GaBi Education license to perform LCA and a free license to obtain Ecoinvent inventory data.

3.4 Application of the method in Russia

In Russia, very little research has been done on the topic of LCA of waste management system. One of the main reasons is lack of statistical databases of applied technologies and harmful effects as a result of their work, and moreover the lack of domestic software products for LCA. Among the problems of inventory data collection, it is possible to highlight:

- difficult access or lack of access to environmentally relevant information available to competent government services;
- reluctance of enterprises and organizations to disclose information on environmental impact;
- insufficient differentiation of data on environmental impacts from enterprises.

An important problem in the development of LCA in Russia is also the insufficient government attention to environmental activities and the lack of motivation of industrial enterprises to reduce their environmental footprint. The problem of lack of reliable data on applied technologies is supposed to be solved by applying foreign data, which may differ from the actual situation in Russia.

However, life-cycle assessment studies, including LCA of waste management, are increasingly being conducted around the world and are an important analytical tool for choosing future developments in the industry. Due to the changes taking place, the LCA method in Russia has great potential for development and application.

One of the works on LCA of waste management system in Russia was the work of Tulohonova and Ulanova for Irkutsk in 2013 (Tulohonova and Ulanova, 2013). The paper considered the impact of the integrated system of solid municipal waste management from the perspective of resource conservation, environmental, economic and social aspects. Several scenarios were compared with the existing waste management system at that time.

In 2013 J. Kaazke from the Technical Institute of Berlin analyzed different MSW treatment scenarios for two Russian cities: Khanty-Mansiysk and Surgut. The aim of the study was to determine the impact of waste composition and transport logistics on the assessment results and to compare developed waste management scenarios with the existing system using the LCA methodology. The developed scenarios were based on the application of different MSW treatment methods, namely incineration, aerobic mechanical-biological treatment (MBT), anaerobic MBT with disposal of residual components in the landfill. The conclusions from the results were the same for both cities: the sorting and separate treatment of different types of waste significantly increases the ecological efficiency of the waste management system. Waste composition can have a major impact on the results of the study, for example, an increase in the percentage of organic waste leads to increased greenhouse gas emissions as a result of its decomposition. As a result of the LCA, it was found that the best scenarios for both cities are incineration of waste, application of anaerobic MBT and establishment of recycling rates around 20% (Kaazke et al., 2013).

Waisman et al. assessed 19 MSW life cycle scenarios based on resource, environmental and economic criteria for Perm city. The preferred MSW management scenario included separate collection of waste, transportation of waste through TS, sorting in a composting plant with recovery of recyclable materials and composting of organic matter (Tulohonova and Ulanova, 2013).

There were no LCA of MSW in Moscow. However, with the reform of the waste management system, it is expected that interest in the LCA of MSW management and assessment of different waste treatment scenarios will increase and the globally recognized method will be used in Russia.

4 LIFE CYCLE ASSESSMENT OF WASTE MANAGEMENT SYSTEM IN MOSCOW CITY

4.1 Materials and methods of the study

Life cycle assessment of MSW management system in Moscow is carried out according to the methodology established in ISO 14040-2006 " Environmental management – Life cycle assessment – Principles and framework" and ISO 14044-2006 "Environmental management – Life cycle assessment – Requirements and guidelines". Waste management model is created using GaBi LCA software (version 7), widely applicable worldwide (Herrmann and Moltesen, 2015). For life cycle impact assessment, CML 2001 (January 2016) is used, Europe's most widely used method of impact assessment, which simulates the categorization of different substance streams into specific impact categories and results in easy-to-analyze units of measurement.

The existing situation of MSW management is modeled on the basis of data from the territorial scheme for Moscow. For 2020 the targets are 83,8% for waste disposal at landfills and 16,2% for other treatment methods. By 2024 it is planned to reduce the share of landfill waste to 64%. With the introduction of new waste incineration plants, the percentage of thermal hazard reduction of MSW waste is expected to increase from the existing 3.8% to 17.6%. As for recycling, its share will increase by only a few percent. Figure 4 shows the targets for these two years.

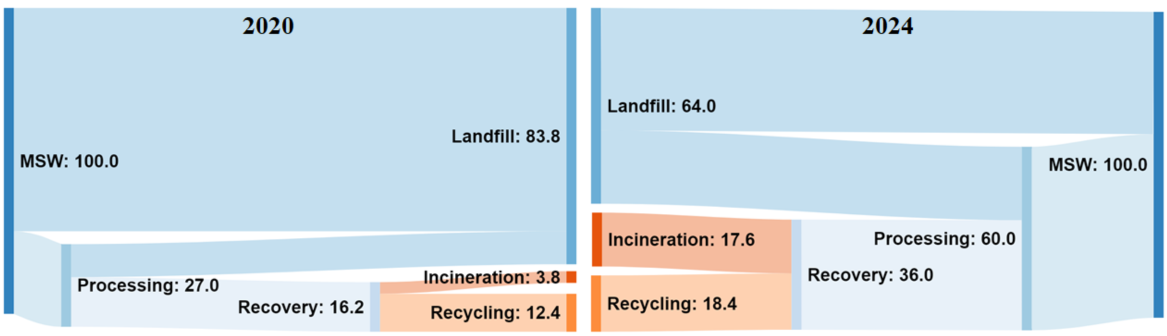

Figure 4 – Targets for waste hazard reduction, utilization and disposal of MSW of Moscow for 2020 and 2024

4.2 Rationalization of data

Detailed information on Moscow waste streams for the next 10 years is available in Appendix 8 of the territorial scheme of Moscow (Official website of the mayor of Moscow, 2019). It was used to create a balance of waste streams in 2020. Based on the results of analysis of the data obtained, it turned out that 100% of the MSW generated in Moscow are sorted before being disposed of and incinerated. This statement is considered incorrect, as the waste processing (sorting) target for 2020 is at least 27%. As a result of this error in the source of initial data, the percentage of waste recycled turns out to be twice higher - about 24% compared to the target of 12.4%. Due to these apparent inaccuracies, the results obtained have been modified with respect to the targets in order to bring the system under analysis closer to the real situation and the authorities' plans for its management. For comparison, in the Strategy of industrial development for processing, utilization and hazard reduction of production and consumption waste until 2030, it is noted that according to statistical reporting, the total amount of waste coming to waste sorting centers in 2016 was 8.9% of the volume of MSW transported from the territory of urban areas. This confirms the fact that 24% is an overstated and unreal value.

The changed results were obtained as follows: the percentage of thermal hazard reduction of MSW based on Annex 8 of the territorial scheme was calculated - about 7.4% of the total amount of waste, the percentage of waste processing was accepted as the same as in the target indicators - 12.4%, and the remainder, i.e. 80.2% were directed to landfill. Thus, the image is obtained, closer to the targets stated in the document. The results for 2020 are summarized in Table 2.

Table 2 – Changing system parameters in relation to 2020 targets

Rationalized data for 2020		Targets for 2020	
Share of landfilled MSW, %	80.2	Share of landfilled MSW, no more than, %	83.8
Share of utilized MSW, %	19.8	Share of utilized MSW, no less than, %	16.2
• of which hazard reduction of MSW, %	7.4	• of which hazard reduction of MSW, no less than, %	3.8

When calculating the balance of waste flows in 2024, the same problem arose, and in addition to it, about 400 thousand tons of waste, i.e. 5% of the total volume, were not taken into account in the balance of flows, the method of their disposal is unknown. The results of calculations for 2024 have been changed in the same way as for 2020. The share of incineration in the total forecasted MSW generation is calculated, the percentage of recycled waste is assumed to be 18.4%, the share of disposal is calculated with taking into account these results. The obtained ratios do not contradict the targets, but even represent more successful their achievement. The results of the rationalization are summarized in Table 3.

Table 3 – Changing system parameters in relation to 2024 targets

Rationalized data for 2024		Targets for 2024	
Share of landfilled MSW, %	57.2	Share of landfilled MSW, no more than, %	64.0
Share of utilized MSW, %	42.8	Share of utilized MSW, no less than, %	36.0
• of which hazard reduction of MSW, %	24.2	• of which hazard reduction of MSW, no less than, %	17.6

All waste flows in the system are directed to sites specified in official documentation. To apply the rationalized results to the flows, it is assumed that all waste arriving at the waste sorting centers is sorted, but not all MSW arriving at KPO is sorted before landfill. Thus, in 2020, 10.6% of recyclables are recovered at Moscow sorting stations and only 1.5% is sorted at KPO. In 2024, 16.2% of recyclable fractions of waste are separated at sorting and transfer stations, while KPO accounts for 2.2%.

To reflect the existing MSW flow map of 12 administrative districts in Moscow, schemes are drawn, which are shown in Appendix I, Figure 1, 2, 3. The first diagram reflects the waste flows transported by rail after waste transfer at 4 TS. The second scheme depicts those flows that are sorted in individual sorting centers and then transported by lorries to the disposal sites. The third scheme reflects the flows, which are routed from the administrative districts, directly to the objects of disposal or thermal waste hazard reduction.

4.3 Goal and scope of the study

This work is primarily aimed at assessing the environmental impact of the existing MSW management system in Moscow for 2020 and its expected changes by the end of 2024. In addition, based on the high potential of organic waste treatment to reduce methane emissions from landfills, prospective organic treatment methods will be simulated.

Additional research questions that need to be answered:

1. What impact does the existing MSW management system in Moscow have on the environment?
2. How does the impact on the environment from the expected changes in MSW management system for 2024 change according to the territorial scheme of Moscow?
3. Which MSW fractions have the greatest contribution to the existing negative impact on the environment?
4. Which processes have the greatest impact on the environment?
5. Which waste fractions have the greatest potential to reduce the negative impact on the environment?

In this study 3 scenarios of MSW management in Moscow will be considered. Two of them, Scenario 0 and Scenario 1, are based on 2020 and 2024, respectively, and the 3rd scenario is the introduction of additional treatment of organic fraction, which is divided into 2 sub scenarios: Scenario 2.1 - treatment of organic fraction at composting plant; Scenario 2.2 - treatment of organic fraction at anaerobic digestion plant. For 2020, the mass of MSW generated is expected to be 8 100 000 tons. For 2024, some increase of 8 300 000 tons of MSW is estimated. However, the MSW mass increase was not considered in the study to keep the functional unit on the same level for the comparability reasons as explained later.

The function of the simulated system is the environmentally friendly management system for municipal solid waste. Since it is impossible to compare the negative impact of the two systems with different volumes of waste, the functional unit of the study is MSW treatment, formed in 12 administrative districts of Moscow in 2020. For the 2024 scenario, all masses of flows will be corrected and converted to the value used as a functional unit. Thus, the 2024 model will present an alternative scenario that could be implemented in 2020 without changes in the amount of waste generation. The following impact categories were selected for assessment: global warming potential (GWP) over a 100-year span, acidification potential (AP) and eutrophication potential (EP).

According to ISO 14044, allocation methods should be avoided in order to prevent inaccurate results. In this paper, allocation is not used and a system expansion is used instead. In other words, the substitution of products on the market with products generated from the recycling and utilization of municipal solid waste fractions is simulated. For example, recycled granulated PET will replace the primary product on the market and compost will replace artificial fertilizers. Typically, in models where the waste management system is well developed, incineration plants generate electricity and heat and substitute energy from the grid. However, in Russia, MSWI plants are not yet considered as a source of electricity generation and is not connected to the grid. Waste incineration plant energy utilization as well as landfill gas collection and utilization are not included in the simulated scenarios, but are modeled in sensitivity analysis in Section 4.6.1.

In order to compare the modeled system with any other LCA on this topic, it is necessary to clearly understand which criteria are included in the model under study and which are not. In order to specify the criteria covered and those excluded from the system, the system boundaries are defined. The life cycle of waste starts from the generation of it at a consumer of goods and services place, collection at special container sites, transportation and treatment, and ends with disposal. The approach, which covers all stages of life from generation to final disposal, is called "bin to grave".

In this study, the stage of generation and collection at the container sites is not assessed. As mentioned before, according to the Government Resolution No. 1156, the regional waste operator is responsible for MSW from the moment it is loaded into the waste truck, so the system is modeled from the moment of loading the mixed and separately collected MSW into waste trucks to the stage of final disposal. It is important to note that only the stages preceding the stage of distribution and sale of this product are considered for substituted goods on the market. This approach is called "bin to gate". The system boundaries for the modeled system are shown in Figure 5.

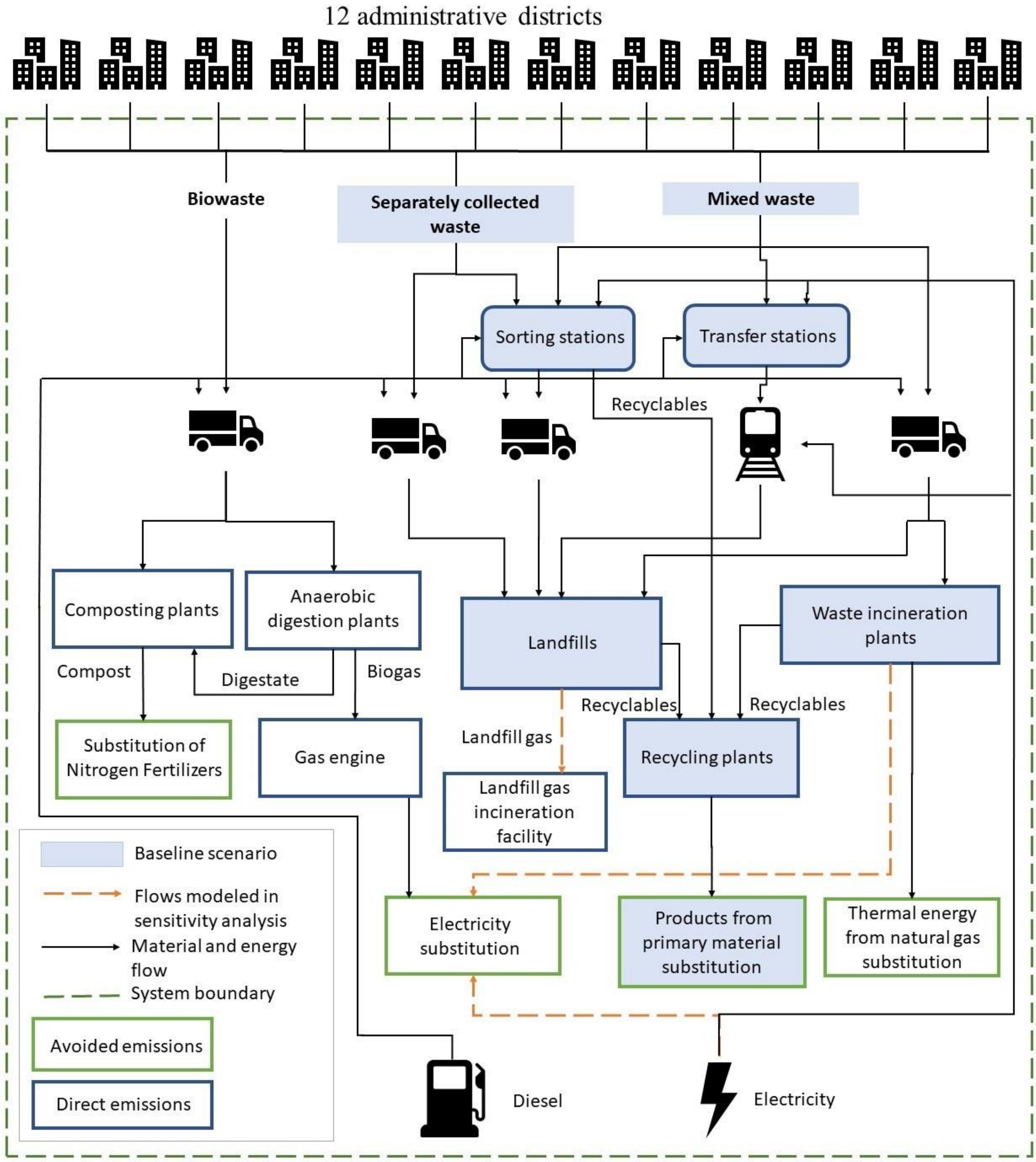

Figure 5 – Systemic boundaries of the study

The system receives MSW from 12 administrative districts of Moscow. All the flows can be grouped into three streams: mixed waste, separately collected waste and, in the perspective of modernization of the system, into a separately collected biowaste fraction of MSW. Part of the mixed and separately collected waste is sent to sorting stations within the city, the other part - to the Moscow region. Both flows are sorted but differ in the efficiency of recovery of secondary resources. A small percentage of mixed MSW is sent to incineration plants, the remaining waste is sent either through waste transfer stations on railway routes or in special automobile transportation to KPO. Some of the waste not sorted in the sorting stations is treated there and then landfilled. The separately collected fraction of biodegradable waste, which is only present in Scenarios 2.1 and 2.2, is sent either to composting plants or to anaerobic digestion plants, with further composting of the resulting digestate. All secondary materials recovered from the waste is sent to recycling and manufacturing plants where it is possible to produce the product using recycled materials. The diagram also shows the flows of materials and energy required to perform the simulated processes. It shows the products generated by the above recycling methods and the products that they can replace on the market.

This work has temporary and resource limitations. Due to the lack of primary data for many waste management processes in Moscow, data for the inventory analysis are based on secondary sources of information. First of all, such sources are the territorial scheme of waste management in Moscow, the Strategy of industrial development for processing, utilization and hazard reduction of production and consumption waste until 2030, various literature sources and GaBi (Sphera, 2020) and Ecoinvent databases (Ecoinvent, 2019).

4.4 Description of the scenarios

For the analysis of the Moscow MSW management system 3 scenarios were developed. The baseline Scenario 0 reflects the current situation as of 2020 and is based on the data presented in the territorial scheme. Scenario 1 simulates the system taking into account changes, which, according to the territorial scheme, will occur by 2024. Input data for these two scenarios are rationalized, as described in section 4.2. Scenarios 2.1 and 2.2 are alternative and simulate a more optimal waste management system that relies on the assumption that the organic fraction of the waste will be collected separately from the mixed MSW, with a collection percentage of about 20%. In both cases, the organic waste is considered a secondary resource and treated. In Scenario 2.1, composting with compost as a useful treatment product is chosen as a treatment method. In Scenario 2.2, organic waste is sent to an anaerobic digestion plant to produce biogas and digestate. The energy from burning biogas is converted to electrical energy and the digestate is subjected to a similar composting process as described in Scenario 2.1 for final treatment. The treatment methods of waste flows for different scenarios are summarized in Table 4. Appendix II, Table 1 shows the MSW management facilities, as well as the facilities that are planned to be introduced and decommissioned by 2024 according to the territorial scheme of waste management in Moscow.

Table 4 – MSW treatment scenarios

Scenarios	Treatment method		
	Biowaste	Separately collected waste	Mixed waste
Scenario 0	-	According to the ter. scheme for 2020	
Scenario 1	-	According to the ter. scheme for 2024	
Scenario 2.1	Composting	According to the ter. scheme for 2024	
Scenario 2.2	Anaerobic digestion	According to the ter. scheme for 2024	

In the simulated system, the flows shown in Table 5 will be routed from MSW collection sites in Moscow. Their ratios are different for each scenario. For Scenario 0, which corresponds to 2020, the ratio of separated collected waste to mixed waste is about 20:80, in Scenario 1, in 2024 the share of SCW is expected to increase within 5%. Scenarios 2.1 and 2.2, also based on data for 2024, simulate the implementation of separate biowaste collection. It is assumed that 20% of the organic waste, which is part of mixed waste, will be successfully recovered. In this case, the organic waste will be 6.9% of the total MSW.

Table 5 – Shares of MSW collected in different ways

Flow name	Scenario 0	Scenario 1	Scenarios 2.1 and 2.2
Mixed waste, %	79.4	75.8	68.9
SCW, %	20.6	24.2	24.2
Organic waste, %	-	-	6.9

Table 6 shows the distribution of collected waste to processing, utilization and disposal sites. The treated waste is further disposed of at landfills.

Table 6 – Distribution of MSW to waste management facilities

Distribution of MSW to waste management facilities	Scenario 0	Scenario 1	Scenario 2.1	Scenario 2.2
Share of waste sent to transfer station, %	28.8	28.8	26.8	26.8
Share of waste sent to sorting, %	38.0	26.4	25.6	25.6
Share of waste sent to waste incineration, %	7.7	24.5	22.3	22.3
• of which is incinerated, %	7.4	24.2	22.0	22.0
Share of waste sent to KPO, %	25.5	20.3	19.1	19.1
• of which is landfilled, %	24.0	19.0	17.8	17.8
Share of waste sent to composting, %	-	-	6.9	-
Share of waste sent to anaerobic digestion, %	-	-	-	6.9

In MSW sorting process the following secondary materials are extracted: metal, plastic, glass, paper and cardboard. They are recycled and used in the production of new products. Table 7 summarizes the percentages of landfilling, incineration, recycling and biological treatment of waste generated in Moscow.

Table 7 – Landfilling, incineration, recycling and biological treatment of MSW in Moscow

	Scenario 0	Scenario 1	Scenario 2.1	Scenario 2.2
Landfilling, %	80.2	57.2	52.7	52.7
Incineration, %	7.4	24.2	22.0	22.0
Recycling, %	12.3	18.5	18.4	18.4
Biological treatment, %	-	-	6.9	6.9

In most cases, the single processes used in the model are taken from the GaBi 2019 professional database or from the Ecoinvent educational database, version 3.6 2019. The processes included in the model are described in detail further.

4.5 Inventory analysis

4.5.1 Collection of waste

Both by 2020 (Scenario 0) and 2024 (Scenario 1), in most regions of Moscow MSW is collected through a two-bin system, whose task is to segregate recyclable fractions from mixed waste. According to the territorial scheme, the potential for secondary materials recovery from mixed waste is on average 20%, and from SCW about 40%. The work assumes that the recovery potential for separated waste is so low due to the presence of undesirable MSW fractions, especially organic fractions, which contaminate materials and make them unusable for recycling. Since the MSW separation system is only being implemented, part of the population does not comply with the SCW rules and does not use the blue bin for its intended purpose. Changing the habits of the population requires time and organization of various educational and training activities which will result in better separation of recyclables from mixed waste. The efficiency of waste sorting also depends on the type of sorting (manual or mechanical), on the configuration of the sorting line and the fractions extracted at the same time.

The composition of MSW is taken from Table 1, as the basic composition, and the composition of waste in blue and grey bins was calculated. It has been assumed that 40% of the weight of the blue bin for SCW is well sorted waste, and 60% is mixed waste that ended up there by human mistake. In this case the recovery rate by residents for each of the 5 secondary materials was 15%, which corresponds to the recovery rates of some European countries with inefficient separation of recyclable materials (Seyring et al., 2015). The new composition of mixed waste and SCW is shown in Table 8 and Figure 6. In this study, the change in MSW composition by 2024 is not taken into account, but in reality, when the efficiency of waste sorting by the public is changed, composition will be changed.

Table 8 – MSW composition in two bins after implementation of separate waste collection system

Name of the fraction	Mixed MSW %	SCW %
Paper and cardboard	36.1	52.4
Food waste	34.2	18.6
Polymers	5.5	8.0
Glass	4.6	6.6
Textile	5.0	2.7
Wood waste	3.3	1.8
Ferrous metals	2.7	4.0
Leather and rubber	2.8	1.5
Stones	2.8	1.5

Non-Ferrous metals	1.4	2.0
Bones	1.7	0.9

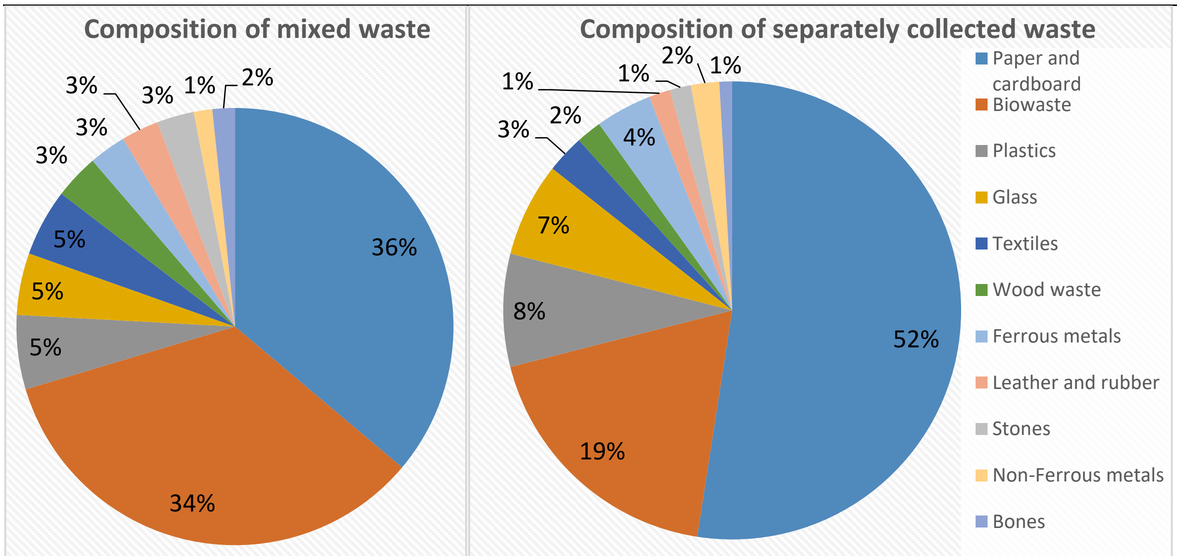

Figure 6 – Composition of MSW after implementation of separate waste collection system

Scenarios 2.1 and 2.2 consider the prospect of introducing a third waste bin for organic MSW fraction. The model is based on Scenario 1, with an assumption that 20 % of the organic fraction of mixed waste is collected separately. The percentage of separated waste is recalculated and summarized in Table 9 and shown in Figure 7.

Table 9 – MSW composition in three bins after implementation of the separate collection of organic waste

Name of the fraction	Mixed MSW %	SCW %	Biowaste %
Paper and cardboard	38.6	52.4	-
Food waste	29.5	18.6	100
Polymers	5.9	8.0	-
Glass	4.9	6.6	-
Textile	5.4	2.7	-
Wood waste	3.6	1.8	-
Ferrous metals	2.9	4.0	-
Leather and rubber	3.0	1.5	-
Stones	3.0	1.5	-
Non-Ferrous metals	1.5	2.0	-
Bones	1.8	0.9	-

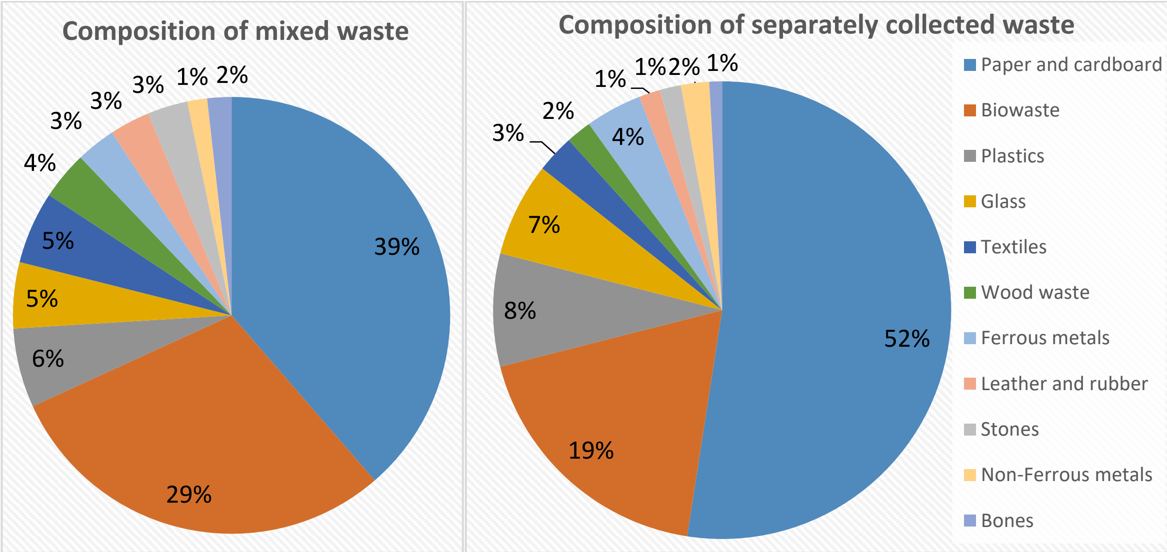

Figure 7 – MSW composition in two bins after implementation of separate collection system for organic waste fractions

The LCA is carried out in accordance with ISO 14040 and 14044 and all processes that are self-modelled must be reflected in detail. For processes taken from the GaBi database, it is sufficient to give the exact name of the process.

4.5.2 Transportation

The boundaries of the system under study start from the moment of loading waste into waste trucks. Separately collected waste is transported separately from mixed waste. For in-city transportation to waste sorting and transfer stations from the GaBi database a truck with the name "Truck, Euro 5, 12 - 14t gross weight / 9,3t payload capacity" is used. The sorted waste is compressed and transported by the lorry named "Truck-trailer, Euro 5, 28 - 34t gross weight / 22t payload capacity". This method of transport over long distances is more appropriate from both an environmental and economic point of view. Nevertheless, the territorial scheme reflects the waste flows from Moscow to the disposal sites without waste processing and transfer to large-capacity transport, so their transportation is modeled using the same "Truck, Euro 5, 12 - 14t gross weight / 9,3t payload capacity". The third method of transportation used in the model is "Rail transport cargo - Electric, extra-large train, gross tone weight 2000t /1452t payload capacity", which is used to transport MSW from TS to landfill sites. Average transport distances have been calculated and shown in Appendix III, Table 1 for all transport flows.

The "Diesel mix at filling station (100% fossil)" process, which includes the stages of diesel fuel production and all related emissions, is taken from the GaBi database for vehicle fuel supply. The rail transport used in the model uses only electrical energy generated by the "RU: Electricity grid mix 1kV-60kV".

4.5.3 Sorting

Sorting of both mixed waste and SCW is carried out at individual waste sorting stations, at waste processing complexes before landfilling, at sorting lines before incineration, and it is planned to introduce sorting at two TS: Nekrasovka and Boynia.

There is no information about the equipment and methods of sorting of each particular station, but based on the data published on the official web sites of the companies (Viva Trans, 2017) (RazDel`ny`j sbor, 2019) (MSK-NT, 2020) (Hartiya, 2017a) (MZhS Group, 2020), it may be concluded that the sorting is mainly manual. At the same time, the report after the visit to KPO "Vostok" (RazDel`ny`j sbor, 2020) reflects that their sorting line also includes a trommel screen, magnet and optical sorting of plastics.

Sorting stations may have different configurations, but in most cases represent a sorting line with a combination of manual and mechanical sorting. Since modelling of each sorting facility is not possible due to the lack of specific information on the equipment used and the extraction of useful fractions, the same values of electricity and diesel consumption per ton of processed waste are taken for all sorting stations. In order to bring the energy consumption closer to real situation, it is assumed that the average sorting station has the following energy consumers: conveyor, drum feeder, magnet, 1-way baler, trommel and rolling stock. The energy consumption is calculated according Pressley et al. (2015) and summarized in Table 10.

Table 10 – Waste sorting process

Flow	Value	Units	Reference
Electricity	3.0	kWh/t	(Pressley et al., 2015)
Diesel	0.7 (0.59)	l/t (kg/t)	

Thus, in the sorting process, it is possible to separate paper waste, plastic types PET and HDPE, glass, ferrous and non-ferrous metals. After separation recyclables are stored in bunkers, pressed and accumulated in wholesale volumes until they are sent to the recyclers (Hartiya, 2017b).

For waste sorting facilities, based on input and output streams of the waste sorting stations from the territorial scheme, the efficiency of recovery of secondary material resources was calculated. The results are summarized in Table 11 and used in modeling the system. Nevertheless, the efficiency seems to be quite optimistic and can differ in reality, but reflect the context of the official document. In 2024, the recovery efficiency of recyclables from SCW is expected to increase by 16-18%, which may result both improvement of public sorting and modernization of sorting lines. In this study, the cause of the efficiency change has not taken into account and the share of recovered secondary materials at sorting station is proportionally increased.

Table 11 – Recovery efficiency of secondary resources at MSW sorting facilities

Sorting facilitie	Recovery efficiency of secondary resources, %			
	2020		2024	
	Mixed waste	SCW	Mixed waste	SCW
LLC «Hartiya»	20	40	20	56
LLC «MKM-Logistika»	20	40	20	56
LLC «EkoLayn», KPSO «Signalnyiy»	25	40	-	56
LLC «MSK-NT»	22	40	22	56
LLC «MSK-NT» MPK-3	20	40	20	56
LLC «Viva Trans»	20	40	20	56
SPM «Dolgoprudnyiy» OOO "EkoLayn"	-	40	-	56
LLC «ZigZag»	13	-	-	-
LLC «MZhS Grupp»	13	-	-	-
LLC «Eko-Alyans», OOO «Eko-Servis»	15	-	-	-
PRK «Boynya»	-	-	20	-
PRK «Nekrasovka»	-	-	20	-
EkoTehnoPark «Kaluga»	25	-	25	58
KPO «Don»	20	-	-	-

KPO «Severnyiy»	20	40	20	56
KPO «Vostok»	20	-	20	-
KPO «Ozernaya»	20	-	-	-
KPO «Progress»	20	-	-	-
KPO «Yuzhnyiy»	20	-	-	-
KPO «Aleksinskiy karer»	20	-	-	-
KPO «Povarovo»	20	40	-	56
KPO «Hrabrovo»	20	-	-	-
KPO «EkoTehnopark»	20	-	-	-
Ekotehprom, MPK-1 «Kotlyakovo»	4	-	4	-
LLC «Hartiya», Rudnevo	5	-	5	-

Since in the balance of flows of the territorial scheme the mass of recovered secondary resources is known, but the mass of each resource type is not known individually, the following assumptions were made for their calculation. From Pressley's et al. article (2015) the recovery efficiencies for the mixed waste stream were selected and multiplied by correction factors, which allowed to obtain a mass of sorted materials equal to that reflected in the territorial scheme. The recovery efficiencies and correction factors used in this work are shown in Table 12. In selecting the correction factors, it was assumed that the recovery rate of metals would remain high as they are extracted mostly through mechanical sorting, unlike other resources that can be extracted manually.

Table 12 – Calculation of recovery efficiency of secondary resources from two waste streams at the sorting station

Fraction	Basis (Pressley et al., 2015)	SCW		Mixed waste	
	Recovery efficiency, %	Correction factor	Recovery efficiency[a], %	Correction factor	Recovery efficiency[a], %
Paper and cardboard	76.0	0.64	48.7	0.5	26.3
Plastics	83.0	0.64	53.2	0.6	33.3
Glass	69.0	0.64	44.2	0.6	27.6

Ferrous metals	88.0	1.0	88.0	0.8	67.7
Non-Ferrous metals	87.0	1.0	87.0	0.8	66.9

[a] Recovery efficiency used in the work

Based on recovery efficiencies, the percentage composition of extracted secondary resources was calculated. This percentage composition is reflected in Table 13.

Table 13 – Composition of MSW sorted recyclable fractions

Fraction	%
Paper and cardboard	64.6
Polyethylene terephthalate (PET)	7.6
High Density Polyethylene (HDPE)	3.9
Glass	8.0
Ferrous metals	10.7
Non-Ferrous metals	5.3

Ekotehprom, MPK-1 «Kotlyakovo» and LLC «Hartiya», Rudnevo sort mixed MSW before the incineration process. It is assumed that shares of recovered materials take values from 4% to 5%, because the main recovered materials before incineration of MSW are metals and undesirable fractions, which are easily removed in the process of manual sorting. The recovery efficiency of metals is the same as reflected in Table 12 for mixed waste flow.

4.5.4 Transfer stations

The waste transfer stations receive mixed MSW, which are then transported to the disposal sites by railway. The model takes into account only the energy consumption of TS electrical equipment. The energy consumption from the grid was calculated and equals 1 kWh/t (MSK-NT, 2020)(Pressley et al., 2015).

In Scenarios 1, 2.1 and 2.2, sorting is performed at «Boynya» and «Nekrasovka» stations in addition to MSW transfers. Energy and fuel consumption at these facilities is modelled similarly to sorting stations.

4.5.5 Landfilling

The emissions of methane from the landfilling were modeled using the IPCC default method (IPCC, 2006) . Scientific literature was used to specify other emissions to air. In the absence of information about the design of each specific facility, the landfill process is simulated similarly for all landfills. It is assumed that landfill gas (LFG) collection and utilization are not included in the process, because there is no information on LFG usage in Russia. It is planned to install a system of landfill gas collection and flaring during landfill reclamation, as the newspapers claim (TASS.ru, 2017) and (RBC.ru, 2019). However, the territorial scheme does not provide information on the application of these technologies to existing landfills, so LFG collection is only covered in the sensitivity analysis in Section 4.6.1.

The IPCC default method allows to calculate the theoretical volume of methane, which will be released by the time the process of decomposition at the landfill is finished. This method does not reflect the amount of gas released each year, but this information is not necessary in this life cycle study. The amount of methane produced by the decomposition of the Moscow waste is calculated according to formula (1):

$$L_0 = \left(MSW_T \cdot MSW_F \cdot MCF \cdot DOC \cdot DOC_F \cdot F \cdot {}^{16}\!/_{12} - R\right) \cdot (1 - OX), \qquad (1)$$

Where L_0 – methane emissions (t/a);

MSW_T – total MSW generated (t/a);

MSW_F – fraction of MSW disposed to solid waste disposal sites;

MCF – methane correction factor (fraction);

DOC – degradable organic carbon (fraction) (kg C/ kg_{MSW});

DOC_F – fraction DOC dissimilated;

F – fraction of CH_4 in landfill gas (IPCC default is 0.5);

16/12 – conversion of C to CH_4;

R – recovered CH_4 (t/a);

OX – oxidation factor (fraction – IPCC default is 0).

Fraction DOC dissimilated is calculated according to equation (2):

$$DOC_F = 0.014 \cdot T + 0{,}28, \qquad (2)$$

Where T – average temperature of the waste pile in landfill (=15 °C).

Only waste that contains organic matter is decomposed, which means that methane is generated from the disposal of this kind of waste. However, different organic fractions decompose at different intensity and velocity. Therefore, for each MSW organic fraction the landfilling process is simulated with different parameters, which are summarized in Table 14. The biowaste fraction has the lowest DOC value per tonne because it contains a large amount of moisture inside.

Table 14 – Modeling parameters for biodegradable MSW fractions (IPCC, 2006)

Fraction	L_0, $tCH_4/t_{MSW}\cdot a$	MCF, (IPCC default)	DOC, kg C/kg_{MSW}	DOC_F	F, (IPCC default)	R	OX, (IPCC default)	T, °C
Biowaste	0.0294	0.6	0.15	0.49	0.5	0	0	15
Paper	0.0784	0.6	0.40	0.49	0.5	0	0	15
Wood	0.0843	0.6	0.43	0.49	0.5	0	0	15
Textile	0.0470	0.6	0.24	0.49	0.5	0	0	15

Since the ratio of methane to CO_2 in LFG is accepted as 1:1, it is assumed that each fraction in the process of decomposition will emit as much carbon dioxide as methane. Other emissions generated at the landfill site are summarized in Table 15. Diesel consumption by on-site bulldozers is also shown in the table. Fuel supply was modelled using a process from the GaBi database "RU: Diesel mix at filling station".

Data on leachate formation volumes from the landfill body are taken from the São Paulo example, as no local data are available. At present, leachate is not collected at most of the landfills in Russia. In recent years, after public protests, a large number of landfills, which had been operating for 40 to 50 years, have been closed and they have started to install wells for leachate collection, which are planned to be taken to the treatment plant (GeoTechProject, 2017).

Table 15 – LCI data for landfill modeling

Parameter	Value	Units	Reference
Diesel consumption of a bulldozer	0.46	dm^3/t_{MSW}	(Liikanen et al., 2018)
CO emissions of a bulldozer	14.0	g/dm^3_{diesel}	(Lipasto, 2012)
NO_x emissions of a bulldozer	21.0	g/dm^3_{diesel}	(Lipasto, 2012)
SO_2 emissions of a bulldozer	0.0081	g/dm^3_{diesel}	(Lipasto, 2012)
CO_2-eq. emissions of a bulldozer	2674.0	g/dm^3_{diesel}	(Lipasto, 2012)
CO emissions of a landfill	15	g/t_{MSW}	(Bjelić et al., 2015)
NO_x emissions of a landfill	68	g/t_{MSW}	(Bjelić et al., 2015)
SO_2 emissions of a landfill	14	g/t_{MSW}	(Bjelić et al., 2015)
HCl emissions of a landfill	0.19	g/t_{MSW}	(Bjelić et al., 2015)
H_2S emissions of a landfill	0.151	g/m^3_{biogas}	(Beylot et al., 2013)
NH_3 emissions of a landfill	0.008	g/m^3_{biogas}	(Beylot et al., 2013)
Leachate generation	0.18	kg/kg_{MSW}	(Liikanen et al., 2018)
Concentration of P in leachate	13.95	mg/dm^3	(Liikanen et al., 2018)
Concentration of N in leachate	3.075	mg/dm^3	(Liikanen et al., 2018)

4.5.6 Waste incineration

As with landfill disposal, incineration is modeled separately for different waste fractions to take into account the morphological composition of MSW. Names of the processes applied: "EU-28: Waste incineration of biodegradable waste fraction in MSW ELCD/CEWEP", "EU-28: Waste incineration of paper fraction in MSW ELCD/CEWEP", "EU-28: Waste incineration of textile fraction in MSW ELCD/CEWEP", "EU-28: Waste incineration of glass/inert material ELCD/CEWEP", "EU-28: Waste incineration of plastics fraction in MSW ELCD/CEWEP", "EU-28: Waste incineration of wood products ELCD/CEWEP".

Incineration or thermal waste hazard reduction results in the generation of bottom ash, flue gases, electrical and thermal energy. The ash is further treated and disposed of, and the flue gases pass through a dry or wet treatment stage. Electrical energy from waste incineration in

Russia is not currently used in the grid. The incineration plant provides energy for its own needs.

4.5.7 Composting

Composting in windrows is the process of producing compost by placing decomposable waste in long rows. These rows are turned over to saturate the mass with oxygen and maintain aerobic processes, and mixed with an additional agent, e.g. sawdust, to ensure an optimal carbon-nitrogen ratio. Cooler and hotter parts of the compost are redistributed equally using wheel loaders or turning devices. The model uses the process "AT: Open windrow composting (incl. compost application and crediting) BOKU" from the GaBi database. No biogas is formed during the process.

It is assumed that the entire volume of compost produced is used on agricultural land as a fertilizer to maintain a balance of carbon and nitrogen in the soil. Emissions from the utilization of compost as a product, as well as avoided emissions, are included in the process.

4.5.8 Anaerobic digestion

Anaerobic digestion is a set of processes by which microorganisms decompose biodegradable material in the absence of oxygen. The process produces biogas, that is a mixture mainly of methane and carbon dioxide, and residual products called solid and liquid digestates. After anaerobic digestion, the digestate is sent for composting and the biogas that is collected and cleaned from H_2S, particles and moisture and directed to a gas engine to generate electricity with an efficiency of 0.37%. The data for the anaerobic digestion and combustion in engine processes are taken from the Ecoinvent database which are listed in Table 16. Process of biogas purification is not included in this study.

Table 16 – LCI for anaerobic digestion and combustion in engine processes

Name in Ecoinvent database	Geographical coverage	Version – system model
Treatment of biowaste by anaerobic digestion	Switzerland	Allocation, cut-off
Heat and power co-generation, biogas, gas engine	Germany	Allocation, cut-off

4.5.9 Plastic recycling

Sorted at SS plastic materials are sent to recycling plants. It is assumed that there are two types of plastics coming: polyethylene terephthalate (PET) and high-density polyethylene (HDPE). Based on Rigamonti et al. (2014), the following ratio between them has been taken to apply: 66% is PET and 34% is HDPE. The inventory analysis data for both processes are taken from the Ecoinvent database, Tables 17.

In 200 km from Moscow, in the city of Tver there is Secondary Polymers Plant, which is one of the largest plants in Russia. It is recycling plastic waste with an annual volume of 20,000 tons (EcoTechnologies, 2019). They produce polyester fibers, packaging tape, sheets and types of packaging with the use of recycled PET. Recycles HDPE can be used in production of waste bins, drainage pipes, compounds and roofing sheets.

First, wrapper parts and contaminants are removed and PET is shredded to a size of 12 mm. Then it dipped into a water tank to separate different types and different density of plastic from PET. The shredded flakes of PET are then processed with 50% sodium hydroxide and the mixture of flakes and alkalis is heated to 200°C. The result of recycling is granulated PET. HDPE is also separated in the water tank, then shredded and melted for further polymer recovery. The result of recycling process is granulated HDPE.

Table 17 – LCI data for plastic recycling processes

Name in Ecoinvent database	Geographical coverage	Version – system model
Polyethylene terephthalate production, granulate, bottle grade, recycled	Switzerland	Allocation, cut-off
Polyethylene production, high density, granulate, recycled	Switzerland	Allocation, cut-off

For the analysis of the avoided emissions, plastic production processes from the GaBi database are used, namely: "EU-28: Polyethylene terephthalate bottle grade granulate (PET) via PTA" for PET and "DE: Polyethylene High Density Granulate (HDPE/PE-HD) Mix" for HDPE.

4.5.10 Glass recycling

One recycling process is simulated for glass of all colors. Like others, it relies on information from the Ecoinvent database. A small percentage of sand, as well as sodium carbonate (Na_2CO_3), limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) can be added to the cullet entering the furnace to produce a homogeneous melted mass without bubbles. Ecofys (Neelis et al., 2009) notes that the main emissions from glass processing come from energy consumption (85-90%). The inventory analysis data about the process is presented in Table 18. The result of glass recycling is container glass. As a primary production process, "EU-28: Container glass" is taken from the GaBi database.

Table 18 – LCI data for glass recycling process

Name in Ecoinvent database	Geographical coverage	Version – system model
Packaging glass production, green	Germany	Allocation, cut-off

4.5.11 Paper recycling

In paper production, a large number of organic and inorganic chemical agents are used to give the product its consumer properties. To simulate waste paper recycling, the process, which utilizes 100% recycled material, is taken from the Ecoinvent database. The recycling product is uncoated paper. A similar process from the Ecoinvent database that does not use recycled paper is taken as a preventative process for the primary production of uncoated paper, Table 19.

Table 19 – LCI data for paper recycling process

Name in Ecoinvent database	Geographical coverage	Version – system model
Paper production, woodfree, uncoated, 100% recycled content, at non-integrated mill	Canada	Allocation, cut-off
Paper production, woodfree, uncoated, at non-integrated mill	Europe	Allocation, cut-off

4.5.12 Metal recycling

Metal recycling saves a significant amount of energy compared to its primary production. In this study it is assumed that 67% of the resulting metal fractions are steel and 33% are aluminum.

In steel production, three methods of melting are most common: in a blast furnace, using an oxygen converter and an electric arc furnace. The blast furnace and oxygen converter represent the primary steelmaking process, with the option of adding steel scrap at the converter stage. By contrast, the electric arc furnace can use steel scrap as the main raw material and can complement the blast furnace and converter processes.

A unit process "EU: Steel sections worldsteel" from the GaBi database was used to simulate the steel recycling process. It includes the operation of both a blast furnace and an electric arc furnace. The result of this process is the production of steel sections.

Only the blast furnace process is used to calculate emissions avoided by steel scrap recycling. The process from the GaBi database for the production of "EU: Steel plate worldstee" is considered the most accurate in calculating greenhouse gas emissions. According to Pardo et al. (N. Pardo, J.A. Moya, 2013), plate and section steel require approximately the same amount of energy for operation and their emissions can be roughly considered the same.

Aluminium recycling is simulated using the "EU28+EFTA: Aluminium refining: casting alloy ingot from scrap (2010) European Aluminium" process from the GaBi database. The process "EU-28: Aluminium casting alloy ingot mix" is used to simulate primary aluminium production.

4.5.13 Electricity consumption from the grid

There is a process in the GaBi database that simulates the generation of electricity from the Russian electricity grid. Emissions from exploration, mining, processing, transportation of fuel to power plants as well as combustion and flue gas purification processes are taken into account in the emission calculation. Figure 8 shows the distribution of energy sources in the grid, as reflected in GaBi documentation for the process "RU: Electricity grid mix 1kV-60kV". According to these data, natural gas accounts for about 50% of the output, 18%, 16% and 14% - nuclear energy, hydropower and coal, respectively. Table 20 shows the processes for which energy consumption was simulated.

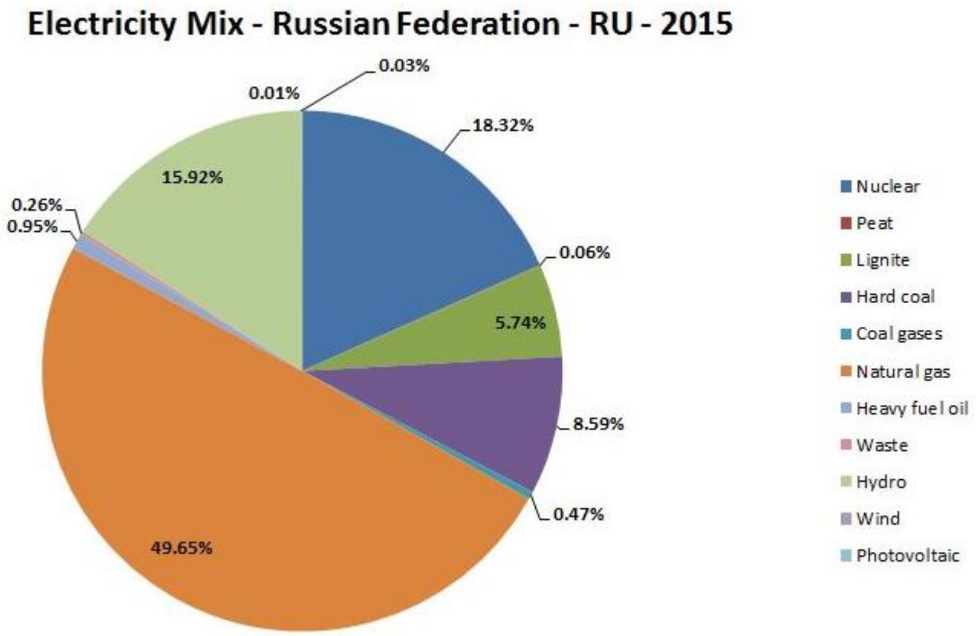

Figure 8 – Energy sources of the Russian electricity grid based on GaBi database documentation

Table 20 – Power consumption in waste management processes

Process	Value	Units	Reference
Sorting stations	3.0	kWh/t_{MSW}	(Pressley et al., 2015)
Transfer stations	1.0	kWh/t_{MSW}	(Pressley et al., 2015)
Railway transport	2.09	kWh/t_{MSW}	(Sphera, 2020)

4.5.14 Diesel fuel production

In processes taken from databases, fuel consumption has already been taken into account in the impact assessment, so "RU: Diesel mix at filling station (100% fossil)" supplies diesel fuel to self-modelled processes, in this case MSW sorting stations, with consumption of 0,7 l/t. The process used includes all stages of the fuel life cycle up to the moment of its use. The process is specialized on Russian fuel.

4.5.15 Avoided emissions

The processes that have been used to assess avoided emissions are summarized in Table 21. Since the composting process has already incorporated the prevented emissions into the result of the impact, no alternative fertilizer production has been used.

Table 21 – Emissions avoided by MSW management system

Primary production process	Process name	Reference
Steel production	EU: Steel plate worldstee	(Sphera, 2020)
Aluminium production	EU-28: Aluminium ingot mix	(Sphera, 2020)
Glass Production	EU-28: Container glass	(Sphera, 2020)
Production of PET	EU-28: Polyethylene terephthalate bottle grade granulate (PET) via PTA	(Sphera, 2020)
Production of HDPE	DE: Polyethylene High Density Granulate (HDPE/PE-HD) Mix	(Sphera, 2020)
Electricity generation	RU: Electricity grid mix 1kV-60kV	(Sphera, 2020)
Uncoated paper production process	Paper production, woodfree, uncoated, at non-integrated mill	(Ecoinvent, 2019)

The data collected are sufficient to simulate a waste management system taking into account the major flows and processes, but without going into a detailed analysis of each process separately. The next step of conducted research is the life cycle impact assessment.

4.6 Life cycle impact assessment

The MSW management system of Moscow is modeled in the GaBi 2019 software. Once the life cycle inventory analysis has been done and the MSW management system has been modeled, the LCIA is performed. Mandatory stages of impact assessment are: selection of impact categories, category indicators and characterization models; allocation of LCI results to selected impact categories (classification); calculation of category indicators (characterization).

According to the study objectives, the impact of the system under study is assessed for three impact categories, namely climate change, acidification and eutrophication. CML 2001, version January 2016, implemented in GaBi software, was chosen as a model of characterization for all three impact categories. Of the two options for the available global warming potential, one that does not include biogenic carbon was selected. By biogenic carbon is meant CO_2, absorbed during plant growth and sequestration in plant tissue. Biogenic carbon can eventually be released back into the air as CO_2 (biogenic carbon dioxide) or CH_4 (biogenic methane).

The procedures for classification and characterisation of the life cycle impact assessment phase are performed in GaBi. In each scenario for each process of the model GWP values were obtained, expressed in kg CO_2-equivalent, AP, expressed in kg SO_2-equivalent, EP, expressed in kg PO_4-equivalent. Conversion of emissions into reference units of impact category occurs at the stage of characterization, by multiplying each type of emissions by its own characterization factor. The main characteristic factors for the impact categories under assessment are given in Table 22.

Table 22 – Characterization factors CML - 2001 (January 2016)

Substance	GWP (100 years) kg CO_2–eq/kg substance	AP kg SO_2–eq/kg substance	EP kg PO_4–eq/kg substance
CO_2	1	-	-
CH_4	25.3	-	-
N_2O	265	-	0.27
NF_3	17200	-	-
NO_x	-	0.5	0.13
SO_2	-	1.2	-
NH_3	-	1.6	0.35
PO_4	-	-	1

The results are grouped into certain process categories and presented in Figures 9, 10, 11 and Tables 23, 24, 25. Direct emissions, i.e. emissions arising from waste management processes, are shown above the horizontal axis, while avoided emissions are shown below the axis. The line in the diagram represents the total values of the impact category indicator, which sum up the direct and avoided emissions.

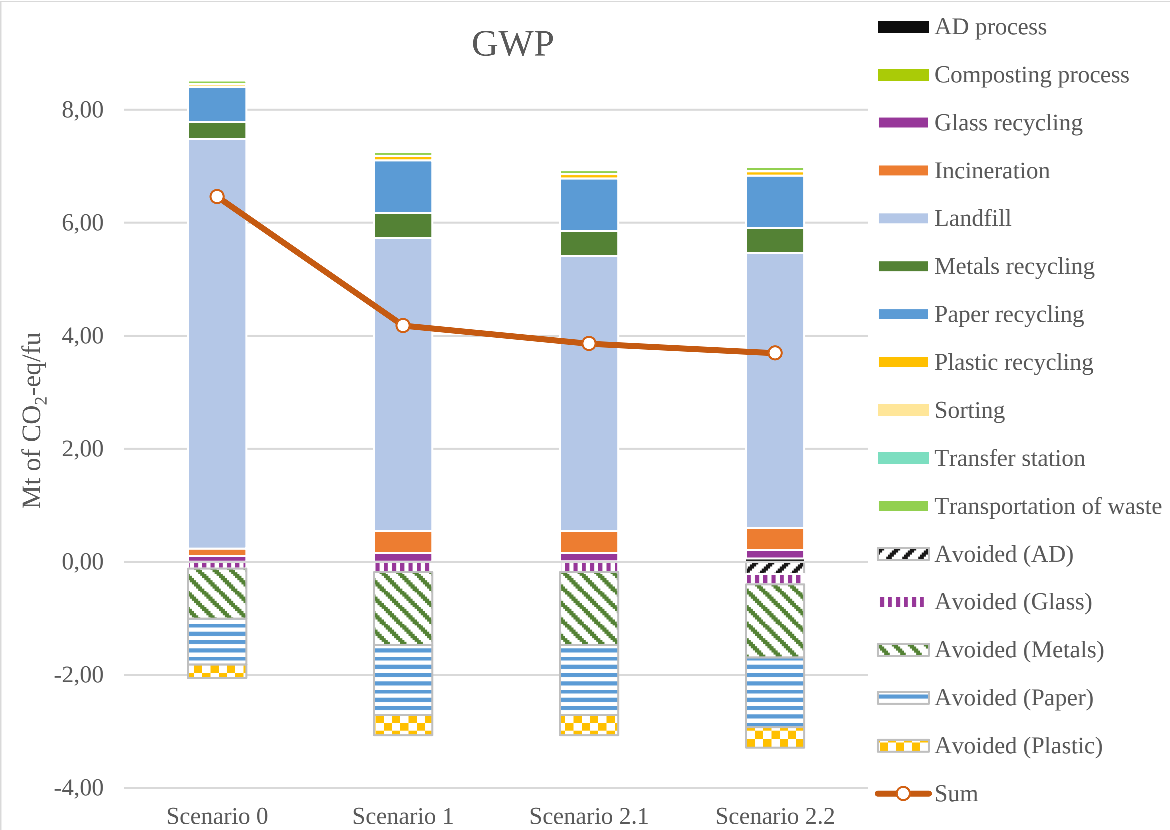

Figure 9 – Global warming potential for simulated scenarios of MSW management system of Moscow city

Table 23 – LCIA results for climate change category

Process	Scenario 0	Scenario 1	Scenario 2.1	Scenario 2.2
Direct emissions, thousand tons of CO_2-eq/fu				
Anaerobic digestion	0	0	0	54
Composting	0	0	7	4
Glass recycling	100	152	152	152
Incineration	133	396	383	383
Landfill	7248	5183	4871	4871
Metal recycling	303	443	443	443
Paper recycling	612	929	929	929
Plastic recycling	48	73	73	73
Waste sorting	7	6	5	5
Transfer stations	2	4	4	4
Transportation	64	61	63	63
Avoided emissions, thousand tons of CO_2-eq/fu				
Glass recycling	-121	-183	-183	-183
Metal recycling	-886	-1295	-1295	-1295
Paper recycling	-814	-1234	-1234	-1234
Plastic recycling	-236	-358	-358	-358
Anaerobic digestion	0	0	0	-219
Total emissions, thousand tons of CO_2-eq/fu	6460	4177	3858	3691

The results of the GWP calculation are presented in the last row of Table 23, entitled «Total emissions», as they are obtained by subtracting avoided emissions from direct emissions. It indicates that under Scenarios 1, 2.1 and 2.2, greenhouse gas emissions are from 35% to 40% lower than in baseline Scenario 0. The growth in the share of incineration in 2024 is leading to some increase in emissions, but the benefits from reduced landfilling are still higher. A minimum amount of emissions is achieved under Scenario 2.2, although the difference between Scenarios 1-2.2 is not as significant as between them and Scenario 0. Scenario 2.2 reduces emissions by 4% compared to Scenario 2.1 and 12% compared to Scenario 1. It is necessary to explain why in Scenario 2.1 composting is not carbon neutral but the total emissions of the system are reduced. The reason is that apart from direct emissions and product substitution on the market, in this case fertilizer substitution, biowaste treatment will prevent biowaste from being landfilled and incinerated. This is also the case in Scenario 2.2.

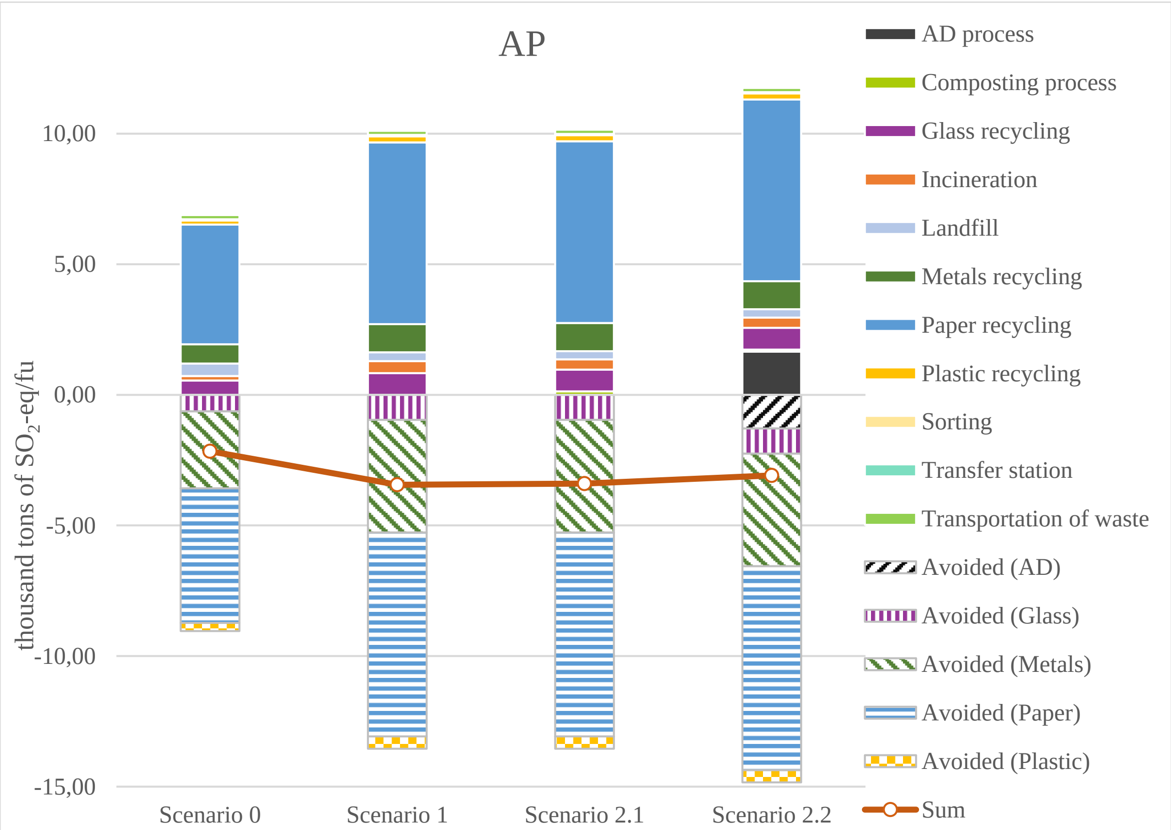

Figure 10 – Acidification potential for simulated scenarios of MSW management system of Moscow city

Table 24 – LCIA results for acidification category

Process	Scenario 0	Scenario 1	Scenario 2.1	Scenario 2.2
Direct emissions, tons of SO_2-eq/fu				
Anaerobic digestion	0	0	0	1652
Composting	0	0	134	83
Glass recycling	549	833	833	833
Incineration	175	459	394	394
Landfill	474	339	313	313
Metal recycling	737	1077	1077	1077
Paper recycling	4585	6955	6955	6955
Plastic recycling	154	233	233	233
Waste sorting	38	32	31	31
Transfer stations	9	23	21	21
Transportation	159	154	157	157
Avoided emissions, tons of SO_2-eq/fu				
Glass recycling	-633	-960	-960	-960
Metal recycling	-2951	-4312	-4312	-4312
Paper recycling	-5146	-7805	-7805	-7805
Plastic recycling	-310	-470	-470	-470
Anaerobic digestion	0	0	0	-1289
Total emissions, tons of SO_2-eq/fu	-2159	-3442	-3399	-3087

The total AP values from Table 24 are negative for all scenarios. This is due to the fact that the avoided emissions of the system are higher than the direct emissions, i.e. the recycling of the secondary materials and substitution of a similar product on the market does not allow for emissions from the life cycle of products manufactured from primary materials. Scenarios 1 and 2.1 avoid almost by 60% of sulphur dioxide equivalent emissions as in baseline Scenario 0. The most significant contribution to AP is made by the primary processes of paper and metal production. Scenario 1 has the lowest acidification potential because, compared to baseline Scenario 0, an increase in the share of recycling (avoided emissions) contributes more than an increase in waste incineration (direct emissions). Comparing Scenarios 2.1 and 2.2, anaerobic digestion has a greater impact on the acidification potential than composting, because the methane combustion process appears. The scenario with composting does not differ much in terms of total emissions from Scenario 1.

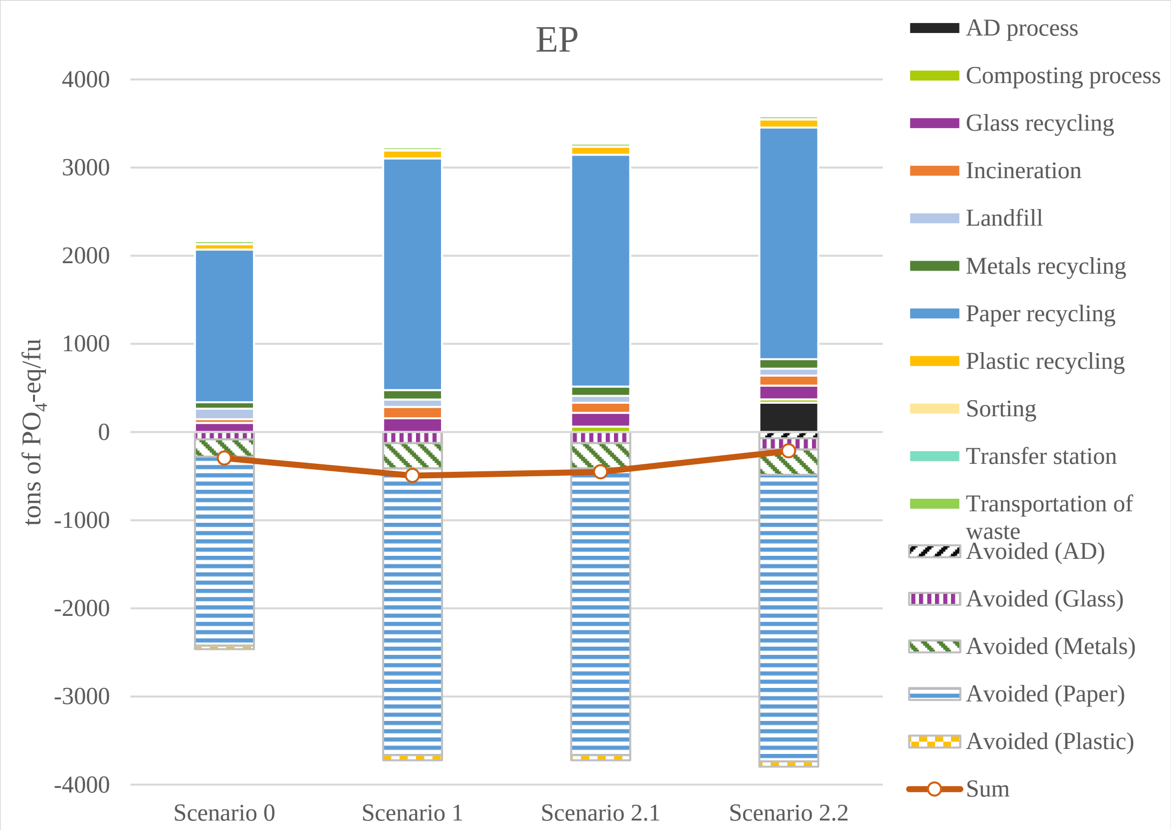

Figure 11 – Eutrophication potential for simulated scenarios of MSW management system of Moscow city

Table 25 – LCIA results for eutrophication category

Process	Scenario 0	Scenario 1	Scenario 2.1	Scenario 2.2
Direct emissions, tons of PO_4-eq/fu				
Anaerobic digestion	0	0	0	333
Composting	0	0	61	38
Glass recycling	103	157	157	157
Incineration	42	127	114	114
Landfill	118	84	78	78
Metal recycling	73	106	106	106
Paper recycling	1734	2629	2629	2629
Plastic recycling	60	90	90	90
Waste sorting	2	2	2	2
Transfer stations	1	1	1	1
Transportation	33	31	33	33
Avoided emissions, tons of PO_4-eq/fu				
Glass recycling	-83	-126	-126	-126
Metal recycling	-196	-287	-287	-287
Paper recycling	-2144	-3252	-3252	-3252
Plastic recycling	-39	-59	-59	-59
Anaerobic digestion	0	0	0	-72
Total emissions, tons of PO_4-eq/fu	-297	-494	-452	-215

The results of the eutrophication potential from Table 25 take negative values in all four scenarios. Paper recycling and production processes contribute the most to the results. Thus, Scenario 1 prevents about 67% of emissions by increasing the share of recycling compared to Scenario 0. By comparing Scenarios 2.1 and 2.2, it is clear that the EP potential is 2 times lower in the 2.1 scenario with composting of biowaste than those from anaerobic digestion. Both scenarios with biowaste treatment produce emissions in this impact category, however, their volumes in Scenario 2.1 do not differ much from those in the optimal Scenario 1.

The main trend among the results of all three impact categories is the reduction of emissions from MSW management system in Moscow by 35-67% in 2024 compared to 2020. As noted earlier, in Scenario 1, landfilling should be reduced by almost 20% due to introduction of new incineration plants and about 6% increase in recycling. Processes which have the large absolute magnitude: for GWP they are landfilling, production and recycling of paper and metals; for AP they are production and recycling of paper, anaerobic digestion as well as metals, glass recycling processes; for EP they are production and recycling of paper, anaerobic digestion and metal production. It should be noted that the main trend of GWP reduction is the reduction of organic fraction landfilling, the growth of recycling also makes a serious contribution to it. As for the other two AP and EP categories, the share of recycling plays a major role but the integration of anaerobic digestion brings significant direct emissions.

Among the options considered, for the climate change impact category (GWP), Scenario 2.2 is the best option, for the eutrophication potential (EP) and acidification potential (AP) the lowest values are in Scenario 1 because it is highly dependent on materials recycling and primary production processes.

4.6.1 Sensitivity analysis

Sensitivity analysis is performed to verify the reliability of the obtained results. If one or more system parameters are changed, the results may change to some extent. First of all, it was decided to check two parameters that could be implemented in the waste management system in the coming years, namely landfill gas flaring and energy recovery at MSWI plants by their connection to the electricity grid and district heating networks.

Landfill gas flaring. As noted earlier, the growth of landfill sites and their use longer than scheduled caused the formation of unpleasant smells in residential areas. That was the reason of numerous protests from residents in Moscow region in recent years. After the landfills were closed, LFG collection systems started to be installed on those sites not for using LFG, but for flaring it. This system was installed at the Kuchino landfill, which was in use from 1964 to 2017 (Government of Moscow Region, 2018).

Sensitivity analysis considers the change in emissions from landfills if the gas flaring system at the new landfills is designed initially rather than at the recultivation stage. At controlled landfills, LFG collection efficiency can reach 60-85% (SCS Engineers, 2008), and for sensitivity analysis a 60% collection rate is taken. The resulting emissions were calculated taking into account the efficiency of flaring, which is 90% (UNFCCC, 2006). The density of methane is equal to 0.668 kg/m^3 (Engineering Toolbox, 2003). The equations of chemical reactions of combustion of gases (3), (4), (5) and mass balance (6) are used to calculate emissions during flaring and the results are summarized in Table 26. Other gases that are contained in LFG, but are not oxidized according to the listed equations, are released to the atmosphere in the same amount as before. Formation of considered combustion products in sensitivity analysis affects only the category of climate change and acidification, eutrophication category is not discussed.

$$CH_4 + 2O_2 = CO_2 + 2H_2O, \tag{3}$$

$$2H_2S + 3O_2 = 2SO_2 + 2H_2O, \tag{4}$$

$$2CO + O_2 = 2CO_2, \tag{5}$$

$$\frac{m_i}{m_j} = \frac{(n \cdot M)_i}{(n \cdot M)_j}, \tag{6}$$

where m – mass of substance;

M – molar mass of substance;

n – amount of substance;

i, j – pre and post reaction substance.

Table 26 – Products of landfill gas flaring

Flow	Value	Units
CO_2 from methane oxidation	2.48	g/g CH_4
CO_2 from carbon monoxide oxidation	1.41	g/g CO
SO_2 from hydrogen sulphide oxidation	1.69	g/g H_2S

Table 27 shows a comparison of changes in GWP results at the landfill site and total system emissions in the presence and absence of LFG flaring. The presence of a gas flaring system would reduce greenhouse gas emissions from landfills by 43%, Figure 12. Since total system emissions depend on many processes, changes in landfill emissions could reduce total emissions in each scenario by 48-57%.

Table 27 – Sensitivity analysis results for LFG flaring at landfills for GWP

Scenario No.	GWP, thousand tons of CO_2-eq/fu					
	Landfill emissions			Total emissions		
	without LFG flaring	with LFG flaring	Change in value, %	without LFG flaring	with LFG flaring	Change in value, %
Scenario 0	7248	4099	-43.4	6460	3311	-48.7
Scenario 1	5183	2931	-43.4	4177	1925	-53.9
Scenario 2.1	4871	2754	-43.4	3858	1752	-54.6
Scenario 2.2	4871	2754	-43.4	3691	1585	-57.1

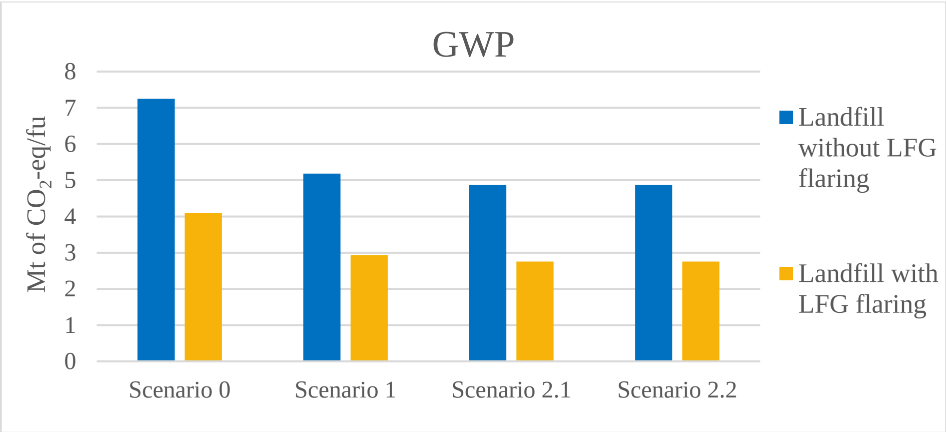

Figure 12 – Sensitivity analysis results for LFG flaring at landfills for GWP

LFG flaring brings minor changes in the AP results, Table 28, Figure 13. Landfill emissions are increased by 8% due to formation of sulfur dioxide in the combustion process. The hydrogen sulfide contained in landfill gas does not make a significant contribution to the acidification category, but when flared it increases the acidification potential. Total system emissions remain negative and increase in the range of 2%. The simulated flaring process does not contribute to the eutrophication category as no such substances are produced during combustion.

Table 28 – Sensitivity analysis results for LFG flaring at landfills for AP

Scenario No.	AP, tons of SO_2-eq/fu					
	Landfill emissions			Total emissions		
	without LFG flaring	with LFG flaring	Change in value, %	without LFG flaring	with LFG flaring	Change in value, %
Scenario 0	474	512	+7.9	-2159	-2121	+1.7
Scenario 1	339	365	+7.9	-3442	-3415	+0.8
Scenario 2.1	313	338	+7.9	-3399	-3374	+0.7
Scenario 2.2	313	338	+7.9	-3087	-3062	+0.8

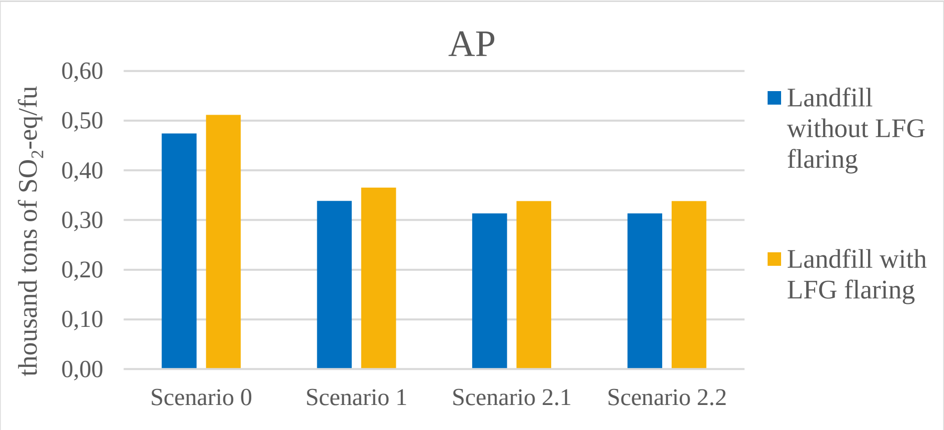

Figure 13 – Sensitivity analysis results for LFG flaring at landfills for AP

Energy recovery at waste incineration plant. The Russian waste management policy is focused on the development of waste incineration. The State Atomic Energy Corporation "Rosatom", which is now the operator of industrial waste management of I and II hazard classes, announced plans to build 25 new incinerator plants with energy recovery (ROSATOM Corporation, 2020). In this case, the plants will supply the power grid and provide energy to the population.

In order to assess the impact of energy production at incineration plants on the system under study, the generation of electricity and heat from the GaBi database is simulated. The avoided emissions from consumption of this energy by consumers were calculated. They are based on the substitution of energy from energy sources listed in Table 29 with energy generated at MSWI plant.

Table 29 – Substituted energy sources in sensitivity analysis for energy recovery

Source of energy	Process name	Reference
Electrical energy generation	RU: Electricity grid mix 1kV-60kV	(Sphera, 2020)
Thermal energy generation	RU: Process steam from natural gas 90%	(Sphera, 2020)

Table 30 shows changes in GWP separately for the incineration process and total emissions of the waste management system for four scenarios. The table and Figure 14 show that when energy is recovered at the MSWI plant, the avoided emissions are higher than direct emissions, so the plant emissions take negative values. Thus, the greenhouse gases of waste incineration process are reduced by 170-180%. The reason for this range is that the scenarios take into account the composition of the incinerated waste and its energy capacity, since it varies in different scenarios, the energy output differ. The total system emissions are reduced by 3.5-18% for different scenarios.

Table 30 – Sensitivity analysis results for energy recovery at MSWI plant for GWP

Scenario No.	GWP, thousand tons of CO_2-eq					
	MSWI plant emissions			Total emissions		
	without energy generation	with energy generation	Change in value, %	without energy generation	with energy generation	Change in value, %
Scenario 0	133	-95	-171.3	6460	6233	-3.5
Scenario 1	396	-327	-182.7	4177	3454	-17.3

Scenario 2.1	383	-304	-179.3	3858	3182	-17.5
Scenario 2.2	383	-304	-179.3	3691	3014	-18.3

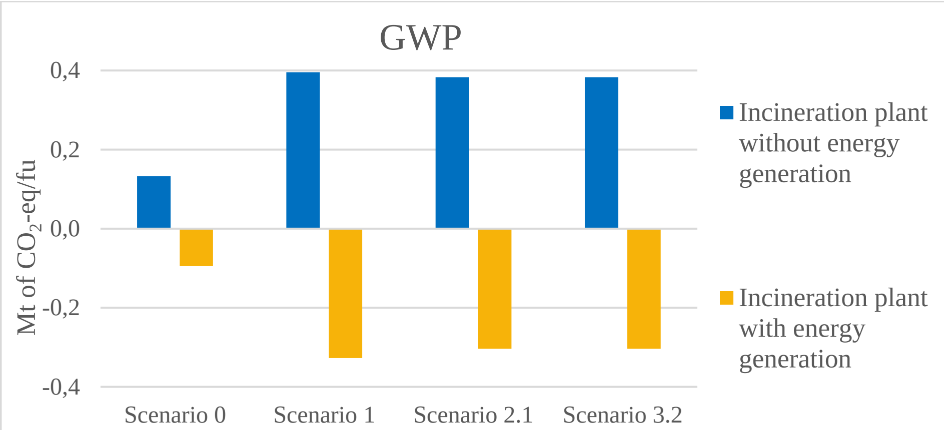

Figure 14 – Sensitivity analysis results for energy recovery at MSWI plant for GWP

Energy recovery has the greatest influence on change in acidification potential. Table 31 and Figure 15 show a strong reduction of AP when energy from the grid is substituted by energy from MSWI plant. In this case the avoided emissions are significantly higher than direct emissions, that makes the resulting emissions of waste incineration negative. This can be explained by the fact that the combustion of fossil fuels, especially coal, produces a large amount of sulfur oxides (Dincă et al., 2010). Sensitivity analysis results in a 400-540% reduction of emissions from the incineration plant with energy supply to the grid. The total system emissions for this category are reduced from 30 to 70% depending on the scenario.

Table 31 – Sensitivity analysis results for energy recovery at MSWI plant for AP

Scenario No.	AP, tons of SO_2-eq					
	MSWI plant emissions			Total emissions		
	without energy generation	with energy generation	Change in value, %	without energy generation	with energy generation	Change in value, %
Scenario 0	175	-535	-405.8	-2159	-2869	-32.9
Scenario 1	459	-1799	-491.9	-3442	-5700	-65.6
Scenario 2.1	394	-1747	-543.0	-3399	-5540	-63.0
Scenario 2.2	394	-1747	-543.0	-3087	-5228	-69.4

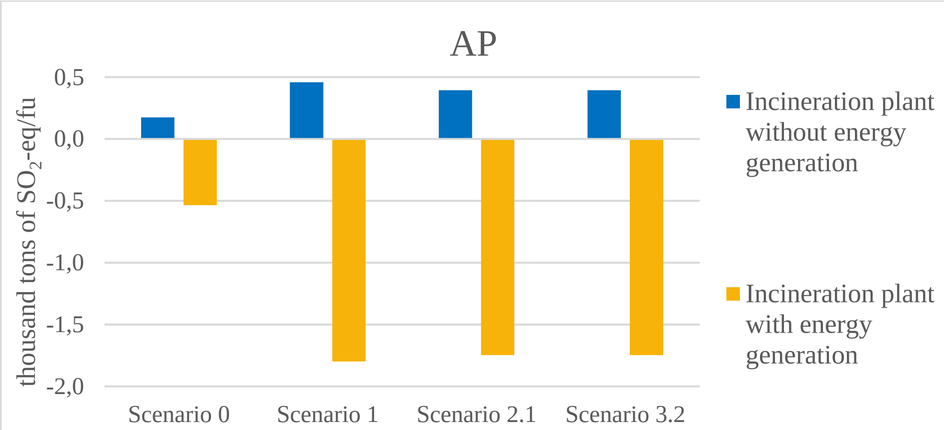

Figure 15 – Sensitivity analysis results for energy recovery at MSWI plant for AP

Eutrophication potential in the process of MSWI plant energy supply to the grid is also considerably reduced. The reason is the prevention of nitrate and nitrous oxide emissions, which occur at different life cycle stages of fossil fuels (Dincă et al., 2010). The results of sensitivity analysis are reduction of aggregate incineration emissions by 175-197% and total system emissions by 25-105% depending on the scenario Table 32, Figure16.

Table 32 – Sensitivity analysis results for energy recovery at MSWI plant for EP

Scenario No.	EP, tons of PO_4-eq					
	MSWI plant emissions			Total emissions		
	without energy generation	with energy generation	Change in value, %	without energy generation	with energy generation	Change in value, %
Scenario 0	42	-32	-175.6	-297	-372	-25.1
Scenario 1	127	-110	-185.9	-494	-732	-47.9
Scenario 2.1	114	-111	-197.4	-452	-678	-49.8
Scenario 2.2	114	-111	-197.4	-215	-440	-104.9

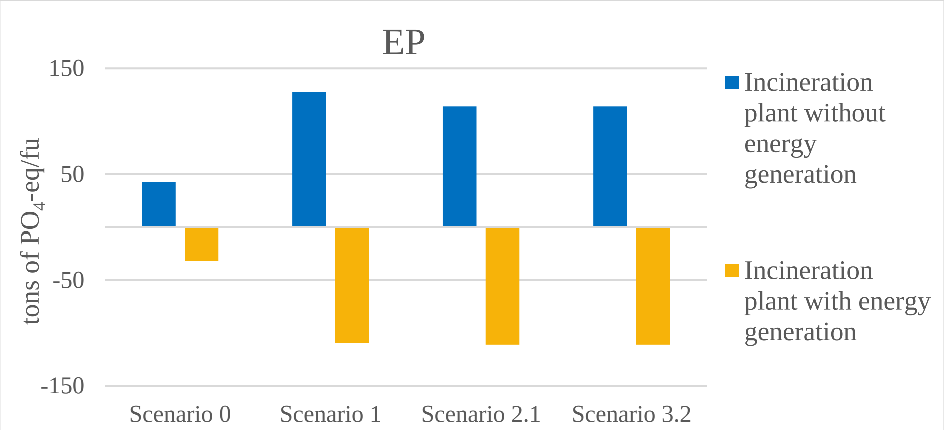

Figure 16 – Sensitivity analysis results for energy recovery at MSWI plant for EP

Obtained sensitivity analysis results do not change the scenario rankings. They do not lead to a preference for one scenario over another. This analysis estimates changes in the absolute value of emissions when the processes described above are implemented in the waste management system.

LFG flaring would reduce the impact on climate change from the system almost twofold, with some increase in acidification potential. It should be mentioned that energy generation during this combustion process would bring more positive changes, but it is not considered in this paper. Energy recovery at MSWI plant reduces the environmental burden in all three impact categories by substituting heat and power from the grid with combined generation. Nevertheless, other categories, especially toxicological ones, need to be assessed in order to confirm the rationality and necessity of implementation of these methods.

4.6.2 Normalization of LCIA results

In order to estimate the scale of emissions from the simulated MSW management system in Moscow, it is necessary to normalize the obtained results. Normalization allows converting the calculated value by dividing it by a reference value, thus the result becomes relative. Calculation is carried out according to the following formula (7):

$$V(a) = \sum_{j=1}^{n} \frac{I_i(a)}{N_i}, \quad (7)$$

where $V(a)$ – normalized impact potential for a specific impact category;

$I_i(a)$ – impact potential for a specific impact category i;

N_i – normalization factor for the specific impact category i.

It can be seen from the LCIA results that the waste management system has positive values of impact only for climate change category. The Paris Agreement in 2015 set out a commitment between countries to keep the global average temperature increase within 2°C of pre-industrial levels and to continue efforts to limit it within 1.5°C (United Nations, 2015)

According to Sitra's study "Targets and options for reducing lifestyle carbon footprints" (Akenji et al., 2019), in order to keep the temperature rise within 1.5°C, it is necessary to strive to achieve the carbon footprint targets per person. By 2030, this target should be 2.5 tons of CO_2-eq/a, by 2040 it should be 1.4 and 0.7 by 2050. According to the same Sitra study, for 2017 the carbon footprint per inhabitant in Finland was 10.4 tons of CO_2-equivalent per year, for China it was 4.2 tons of CO_2-eq/a and for Brazil it was 2.8 tons of CO_2-eq/a.

According to the biennial report (Ministry of Natural Resources and Environment of the Russian Federation, 2019), 1577.8 million tons of CO_2-eq were formed in Russia in 2017, with taking into account land use and forest absorption capacity. The population of the country at that time was 144.5 million (The World Bank Group, 2020). Thus, if calculated per capita, greenhouse gas emissions were 10.9 tons of CO_2-eq per capita. The results of the waste management system can also be visualized as the number of residents, knowing that the population of Moscow is 12.7 million people. Table 33 shows the results of such normalization for the total system GWP results and for the disposal process at landfills.

Table33 – Normalization of GWP results in relation to the Moscow population

Parameter	Scenario 0	Scenario 1	Scenario 2.1	Scenario 2.2
Results of GWP from landfill sites				
Normalized GWP result, number of residents	664 916	475 488	446 837	446 837
Percentage of Moscow population, %	5.2	3.7	3.5	3.5
Results of total GWP of the system				
Normalized GWP result, number of residents	592 653	383 184	353 976	338 614
Percentage of Moscow population, %	4.7	3.0	2.8	2.7

The total emissions of greenhouse gases from MSW management system in Moscow in 2020 are equivalent to annual emissions, which cause 4.7% of the city residents. This illustrates the fact that the waste management system is not the only problem to be solved systematically in order to contain the global temperature rise within the planned limits. About 95% of the carbon footprint is caused by fossil fuel use, consumption of products with high life-cycle emissions, huge transport loads and other sources of greenhouse gases. On average, the global warming potential per capita from Scenarios 1-2.2 decreases by 35% and 43% relative to the baseline scenario, respectively.

4.7 Interpretation of the obtained results

4.7.1 Identification of significant issues

The identification of significant issues is necessary to structure the LCI and LCIA results to identify the most significant processes in terms of contribution to the total emissions from the different considered scenarios. It helps to draw conclusions and provide recommendations according to the goal and scope of the LCA. Figures 17, 18, 19 rank the percentage contributions of process to the direct, avoided and total emissions of the system for three impact categories. The ranking is based on Scenario 2.2 because there are no principal differences in the contribution of repeating processes in other scenarios. But it should be reminded that in Scenario 2.2 about 53% of waste is landfilled, 22% is incinerated, almost 18% is recycled and 7% is treated at anaerobic digestion plant. The composting process is only shown in the total emission diagram, as its emissions cannot be divided into direct and avoided in this model.

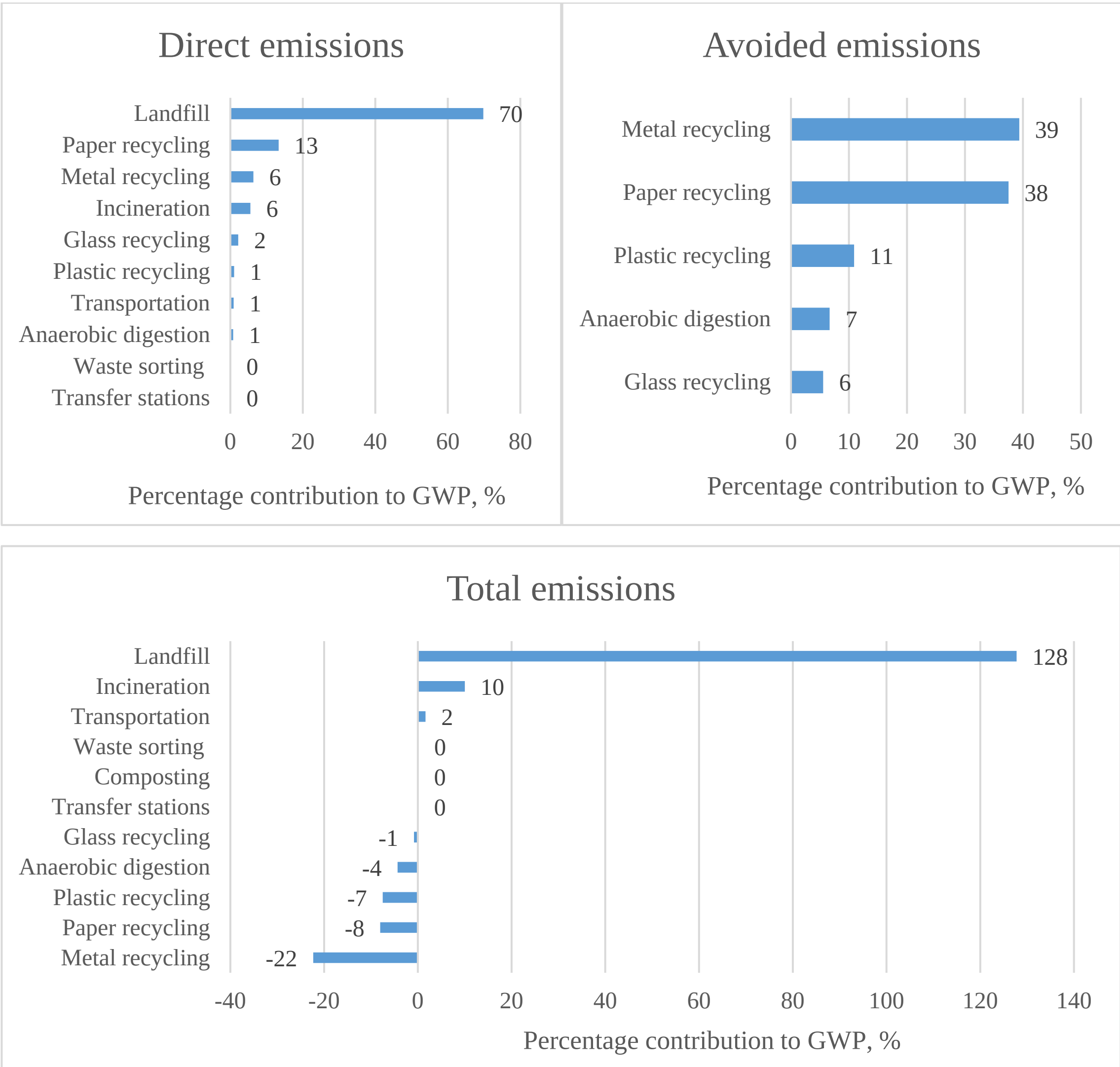

Figure 17 – Direct, avoided and total GWP of MSW management systems in Moscow

The main source of greenhouse gases is the process of anaerobic decomposition at landfills. In order to reduce the environmental burden, it is necessary to reduce the share of landfilling, introduce separate treatment of organic waste and build LFG collection systems. This process is followed by incineration, which is beginning to be widespread in Russia. To reduce the impact from incineration plants, it is necessary to develop recycling infrastructure to reduce the amount of waste reaching the MSWI plants and to introduce combined electricity and heat generation at the plants. Metal and paper recycling contribute mainly to the avoided emissions. In metal recycling, 50-75% less energy can be used than in primary production (Johnson et al., 2008), so even small amounts of recycling make a big difference for the system. Paper recycling contributes so much to the results because it accounts for almost 40% of all waste and high volumes of recycling are modeled in the system.

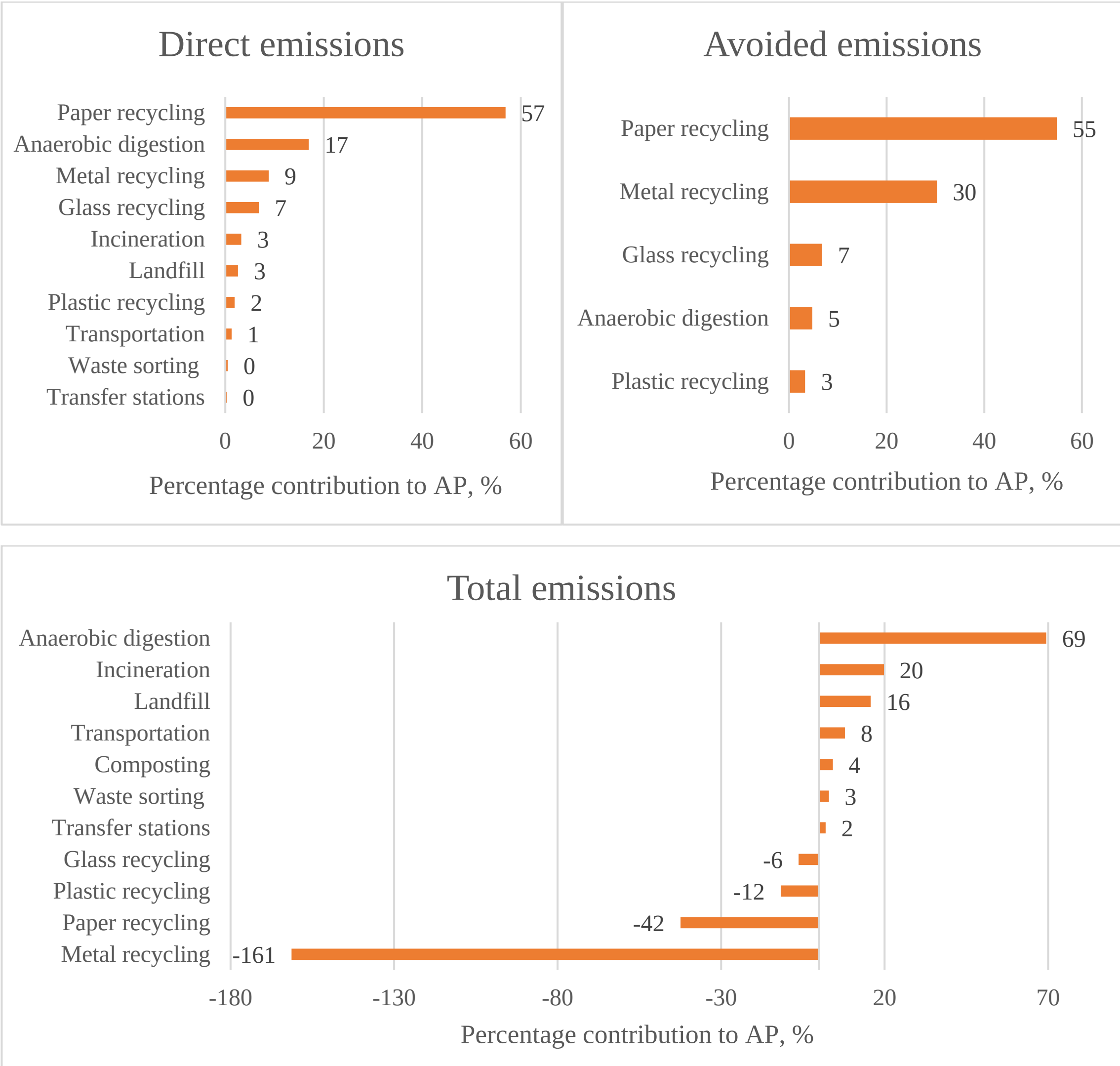

Figure 18 – Direct, avoided and total AP of MSW management systems in Moscow

The most intensive processes in the acidification category are those involving combustion and sulfur oxides emission, i.e. all processes of energy production from fuel. Therefore, the processes that avoid energy consumption, i.e. all recycling processes, reduce the total emissions in this category. Both the recycling process and the primary production process of paper have a large amplitude of emissions in the acidification and eutrophication categories. About 50% of these emissions occur in the processing of pulp (Sun et al., 2018). The process is accompanied by the use of chemicals and containing nitrogen compounds in the waste water. The anaerobic digestion process contributes to the total emissions not only in the gas combustion phase but also throughout the digestor. According to Hospido et al.(2010), in this process phosphates enter the waste water and ammonia is emitted into the air, so in the acidification and eutrophication category the emissions are quite significant.

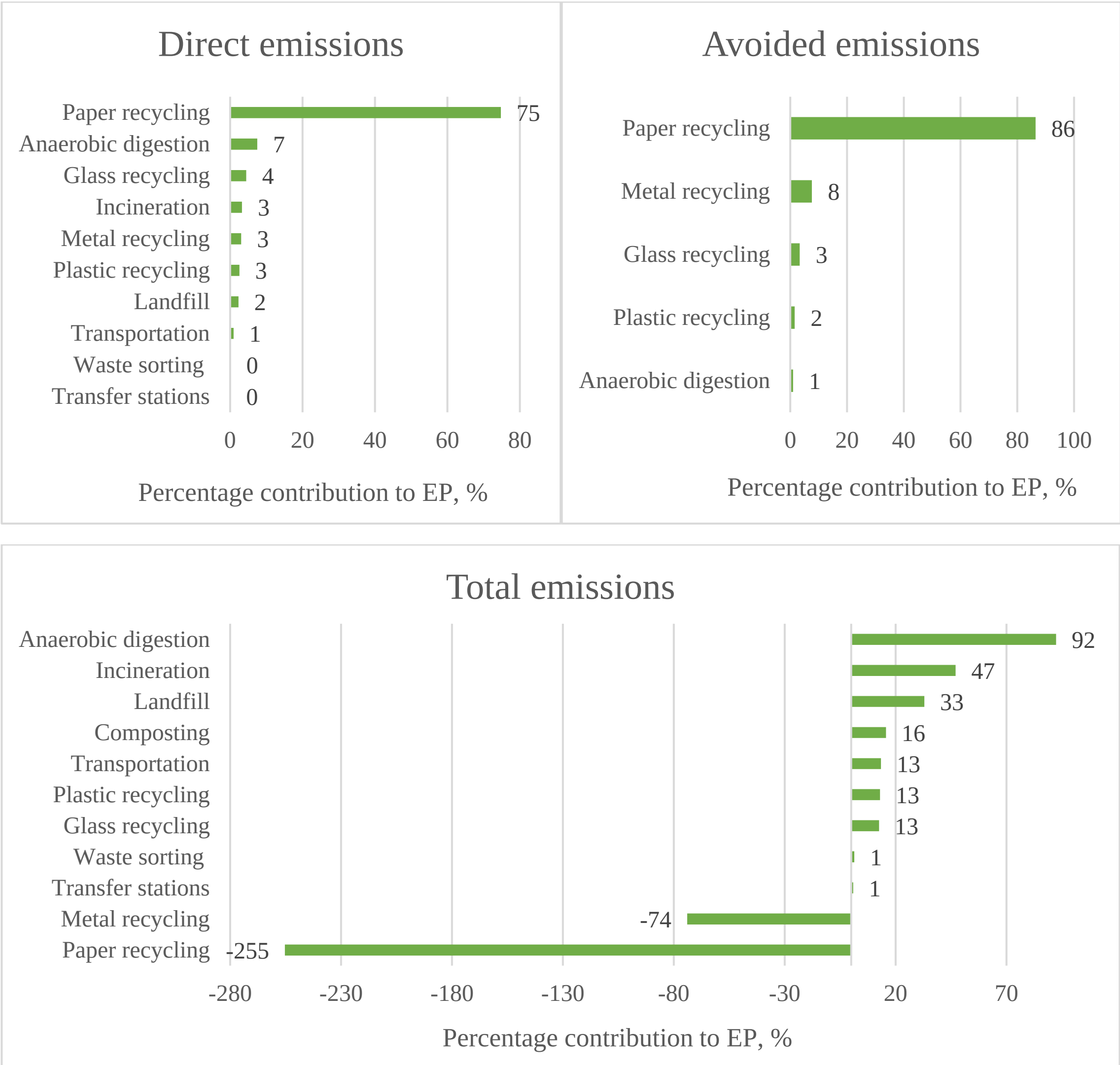

Figure 19 – Direct, avoided and total EP of MSW management systems in Moscow

As already mentioned, one of the main reasons for the high eutrophication potential of paper production is the ammonia content in the waste water after pulp processing. Nitrogen oxide emissions also occur during combustion processes and energy production, so anaerobic digestion and incineration are making a contribution to EP. Landfilling produces leachate with a high content of nitrates and phosphates, so its volume and methods of treatment may have a significant effect in this category.

Since landfilling is the main reason for greenhouse gas emissions, emissions from the organic waste fractions were analyzed. Table 34 contains the methane generation potentials of each fraction as well as total GWP values from disposal of each fraction.

Table 34 – Methane formation potential and GWP from the landfill for different organic fraction of MSW

Fraction	L_0, $kgCH_4/t_{MSW} \cdot a$	GWP, Mt of CO_2-eq			
		Scenario 0	Scenario 1	Scenario 2.1	Scenario 2.2
Biowaste	29.4	1.7	1.3	1.0	1.0
Paper	78.4	4.7	3.3	3.3	3.3
Wood	84.3	0.5	0.3	0.3	0.3
Textile	47.0	0.4	0.3	0.3	0.3

Wood and paper contain a lot of carbon, therefore have great potential for methane formation. Due to the fact that paper accounts for more than one-third of MSW, its landfilling according to this study causes more emissions than biowaste landfilling. Reduction of emissions from disposal requires reduction of organic fraction landfilling, first of all paper and biowaste. That is why the separation of organic fraction in the source of waste generation could be a reasonable solution.

One of the objectives set in the study is to identify MSW fractions, which have the greatest potential to reduce the environmental burden. For this purpose, emission values per kilogram of recycled secondary resources were calculated and reflected in Table 35. They take negative values because they reduce emissions in the system. If recycling of a particular fraction has a greater impact than the primary production process of similar material, the potential for that fraction is not shown in the table.

Table 35 – Emission reduction potentials of secondary resources

Secondary material	GWP	AP	EP
	kg CO_2-eq/kg material	g SO_2-eq/kg material	g PO_4-eq/kg material
PET	-2.0	-1.5	-
HDPE	-1.1	-1.2	-
Paper	-0.3	-0.9	-0.7
Glass	-0.3	-1.1	-
Aluminium	-7.3	-33.5	-1.7

Steel	-1.4	-2.4	-0.2
Biowaste	-0.3	-	-

Metals, and especially aluminum, have the greatest potential to reduce negative impact for the three analyzed categories. Their recycling process is much less energy consuming than primary production and is accompanied by lower emissions because of metal scrap use that can be recycled many times. In two of the three impact categories, plastic ranks second after metals in terms of the emission reduction potential and the potential of PET is higher than HDPE. Recycled paper prevents, like metals, emissions in all three categories under analysis Gutowski et al. give the same ranking to recycling processes that significantly reduce energy consumption (Gutowski et al., 2013). Glass recycling allows reducing GWP and AP. Organic treatment by anaerobic digestion has the potential to reduce impacts only in the climate change category. Composting has positive emissions, so it is not considered in this analysis. Nevertheless, it should be noted that the calculation of the potential for biowaste treatment has taken into account the emissions from the treatment process and the avoided processes, due to energy generation from biogas, but very importantly, it has not taken into account the prevention of landfilling of biowaste. If this parameter were taken into account, the biowaste treatment would have a higher potential.

4.7.2 Completeness and consistency check

The completeness check indicated that most of the simulated processes include all important inventory data in order to draw conclusions from the study results. Assumptions made to simplify the model are considered acceptable for this study.

One of the main assumptions that may lead to underestimated emissions is the simulation of material recycling, primary production and incineration processes that are applied in different countries. The use of these processes does not take into account local conditions and energy consumed by the processes may be produced by sources different from Russian energy sources. However, due to the lack of data on specific processes in Russia and the absence of such data in the GaBi and Ecoinvent databases, it was rational to use international data.

In this study, consistency check is performed for geographical coverage only. The results are shown in Table 36. The modeling of processes based on the experience of the countries listed is consistent with the goals set out in this study.

Table 36 – Consistency check

Process	Geographical coverage
Transfer station	-
Waste trucks	Global - OK
Electric trains	Global - OK
Supply of diesel fuel	Russia - OK
Supply of electricity from the grid	Russia - OK
Waste sorting station	-
PET recycling	Switzerland - OK
PET production	Europe- OK
HDPE recycling	Switzerland - OK
HDPE production	Germany - OK
Incineration plant	Europe- OK
Landfill	-
Composting	Austria - OK
Anaerobic digestion	Switzerland - OK
Combustion of biogas in a gas engine	Germany - OK
Glass recycling	Germany - OK
Container glass production	Europe- OK
Aluminum recycling	Europe- OK
Aluminium production	Europe- OK
Steel recycling	Global - OK
Steel production	Global - OK
Paper recycling	Canada - OK
Paper production	Europe- OK

4.8 Conclusions, limitations and recommendations

The study assessed three categories of environmental impacts: global warming potential, acidification potential and eutrophication potential. In order to draw conclusions on the life cycle assessment of the municipal solid waste management system in Moscow, it is necessary to answer the questions set out in the research objectives.

The environmental impact of the existing MSW management system in Moscow was assessed. In the existing system, 80% of MSW is landfilled, approximately 7.5% is incinerated and 12% is recycled. Baseline Scenario 0 has the highest potential emissions in the global warming and acidification categories. Compared to Scenarios 1, 2.1 and 2.2, its GWP is 35-40% higher and AP is 40-60% higher depending on the scenario. In the eutrophication category, Scenario 0 has the second highest emissions after Scenario 2.2 with anaerobic digestion. Landfill disposal is the most intense source of greenhouse gas emissions. The contribution of landfill emissions to GWP of the existing waste management system is 85% of the direct emissions of the system or 112% of the total emissions, taking into account the avoided environmental burden. Significant emissions are also formed by the recycling of paper and metal, but these processes allow to avoid higher emissions in the primary production of products. The total emissions of the system can be represented as the total carbon footprint of 4.7% of the Moscow population. Sensitivity analysis has shown that if LFG flaring system was implemented, total emissions would be reduced by almost 50%. The sensitivity analysis also showed that the MSW incineration process would be carbon-negative if it provided energy to consumers.

The environmental impact of proposed changes to the MSW management system for 2024 has been assessed. In 2024, Scenario 1, it is planned to reduce the proportion of landfilled waste by approximately 20% by increasing the proportion of incineration and recycling of secondary resources that MSW contains. In terms of climate change impacts, incineration prevails to some extent over landfills, while recycling processes are carbon negative. As a result of these changes, the potential impacts of the system are significantly reduced - by 35% for GWP, 60% for AP and 67% for EP. It is important to note that this scenario has the lowest potential in the acidification and eutrophication category. The main reason for the decrease in its AP and EP compared to 2020 is the increase in the share of recycling, on which the results of these categories are strongly dependent. Further proposals for biowaste treatment in Scenarios 2.1 and 2.2 increase emissions of acidification and eutrophication categories. Total system emissions from these two categories are negative in all scenarios.

As the dominant impact source is landfilling, the majority of emissions are caused by substances that are undergoing anaerobic decomposition. The potential for methane formation and the amount of greenhouse gases generated by the organic MSW fraction, namely food, wood waste, paper and textiles, were analyzed. Calculations show the greatest potential for methane formation in wood and paper, however, paper and biowaste are the main organics in the landfill. If organic waste is collected separately and treated in other ways, the system burden is considerably reduced. Therefore, Scenario 2.1, where biowaste is treated with composting, and Scenario 2.2, where anaerobic digestion is considered as an alternative method, were simulated and assessed. By separating biowaste by about 7% of the total mass of MSW, GWP can be reduced by 5% using composting and by 12% using anaerobic digestion.

As mentioned before, landfilling is the most unsuitable method of waste management and has a huge impact on the impact categories under study. The second process with the highest emissions is incineration. As long as its share is small, these emissions seem relatively small, but as the number of MSWI plants grows, they will increase. Recycling processes in almost all categories, with the exception of some processes in the eutrophication category, take negative values. However, in terms of direct emissions, recycling of paper, metal and glass are the most intense. These processes are associated with energy consumption and paper recycling is also characterized by the formation of contaminated wastewater. However, the emissions from recycling are much less than those from primary production processes and therefore their impact is offset.

The most potential MSW fractions to reduce negative environmental impacts have been identified. Of the separately collected fractions, metals have the highest potential to reduce the environmental impact, especially aluminum. By recycling 1 kg of aluminum, 7.3 kg of CO_2-eq, 33.5 g of SO_2-eq and 1.7 g of PO_4-eq can be avoided. Plastic also has a high GWP and AP reduction potential, of which PET has a higher than HDPE. This is followed by potentials for glass and paper recycling.

Inventory analysis is based on secondary data sources, which is consistent with the purpose and depth of research. To obtain more reliable and realistic results, it is recommended to use information from primary sources. In the absence of data on the composition of Moscow waste, the average MSW composition for the country is used, which may differ to some extent from the real situation. Also, it is worth noting that the baseline scenario is the waste management plan for 2020, which was drawn up in 2019 and may not reflect the real situation.

To build a more holistic picture of the environmental impact, it is recommended to analyze other categories of impact, such as human toxicity and ecotoxicity owing to the emissions of polychlorinated dibenzodioxins and furans. However, the LCIA methods on toxicity are highly uncertain due to the inability to take into account the dose-response mechanisms at the place of emissions generation.

5 SUMMARY

The goal of this work was to assess the impact of the life cycle of the MSW management system in Moscow. Scenarios 0-2.2 were compared with each other, which correspond to the current system, the system planned for introduction in 2024 and the alternative system where organic waste is collected separately from mixed MSW and treated. All questions raised for the study were answered.

The assessment was conducted for the three environmental impact categories and results were obtained in the form of Global Warming Potential (GWP), Oxidation Potential (AP) and Eutrophication Potential (EP). These potentials have been calculated as the difference between direct emissions from MSW management facilities and avoided emissions from recycling.

The modeled waste management system makes the greatest contribution to the climate change impact category. In the baseline scenario for 2020, the largest amount of greenhouse gases is generated - around 35-40% more than in other scenarios. GWP in 2020 is equivalent to the emissions of 4.7% of the Moscow population, assuming that the carbon footprint of one resident is 10.9 tonnes of CO_2-equivalent per year.

Scenario 0 for 2020 has the highest emissions in climate change and acidification categories. The best option in the climate change category is Scenarios 2.1 and 2.2, based on waste management system in 2024 with the only difference in the implementation of biowaste treatment, but Scenario 2.2 with anaerobic digestion is preferred of the two. For acidification and eutrophication categories, Scenario 1 has the lowest potentials. However, AP and EP are negative for all scenarios as the recycling processes have a high level of avoided emissions.

Landfilling, which is the main method of MSW management, is the major source of greenhouse gas emissions, the main of which is methane. The contribution of landfilling to the direct emissions affecting the global warming ranges from 85% in Scenario 0 to 70% in Scenario 2.2. Incineration, a waste management method that will develop in the coming years, currently creates relatively small emissions, but they will grow with the introduction of new MSWI plants. Solutions that would significantly reduce landfilling and incineration emissions are the use of LFG flaring and energy generation at incineration plants.

The most significant contribution to the negative impact is made by organic fractions of waste, especially paper and biowaste, which undergo anaerobic decomposition in landfills. That is why the introduction of separate collection and treatment of biowaste would significantly reduce the burden on the environment from the waste management system. If biowaste, equals to 7% of total MSW mass, is separated in the source of generation and treated, it would be possible to reduce GWP of the direct emissions by 4-7%.

Among the secondary resources, metals have the highest potential for emissions reduction. Plastics, paper and glass are next after metals in terms of emission reduction potential. If the listed MSW fractions are properly sorted on the collection site by the population, the recovery efficiency and the share of recycling will increase. To achieve this, it is necessary to change the habitual attitude of people towards waste, organize various educational and training events for the population over a long period of time.

The results of the study reflect the potential environmental impacts for the three categories of considered scenarios for MSW management in the city of Moscow. The depth of the study corresponds to research objectives and allows to assess the system as a whole, but when analyzing individual waste management processes, deeper research of the inventory data and an assessment of a larger number of impact categories are suggested.

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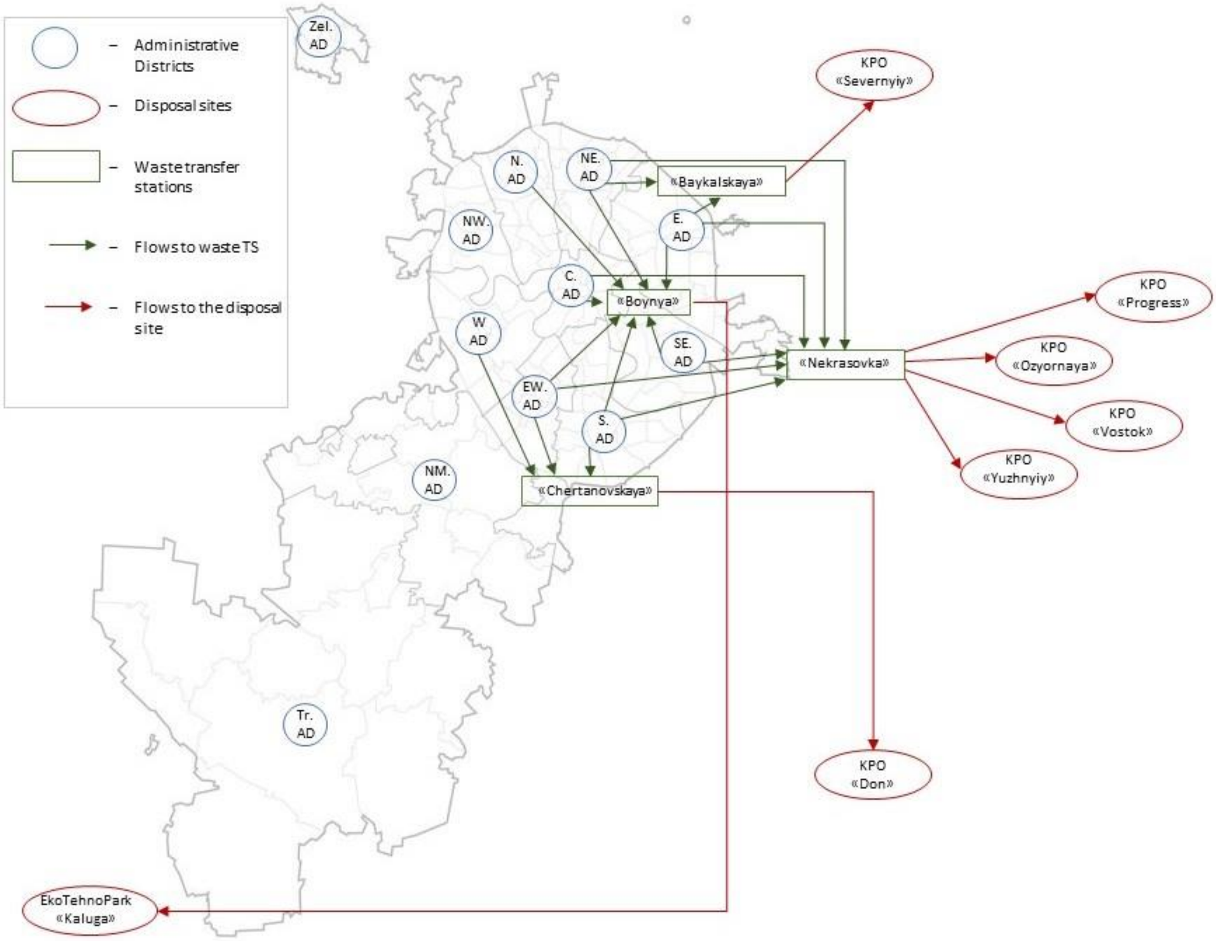
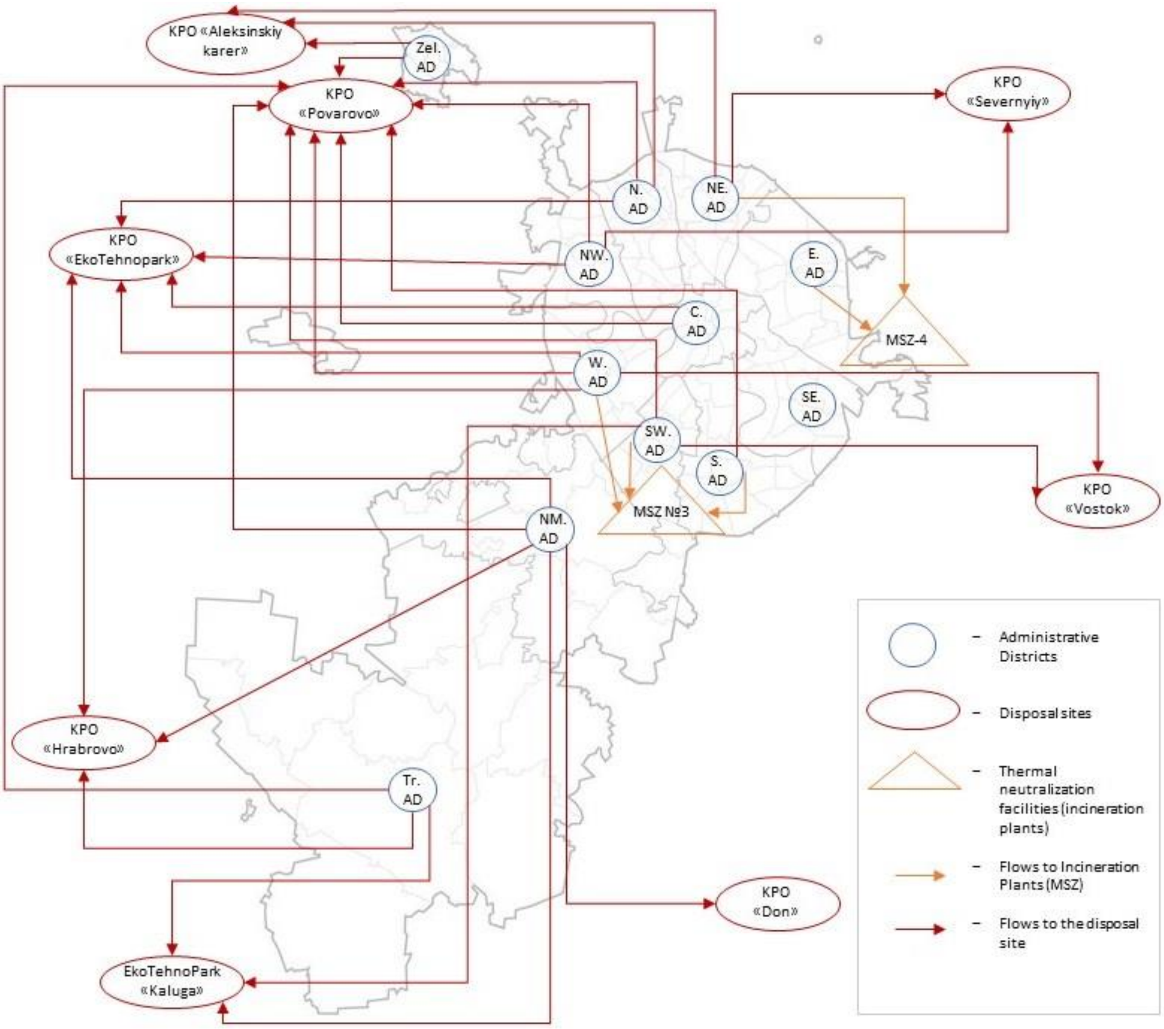
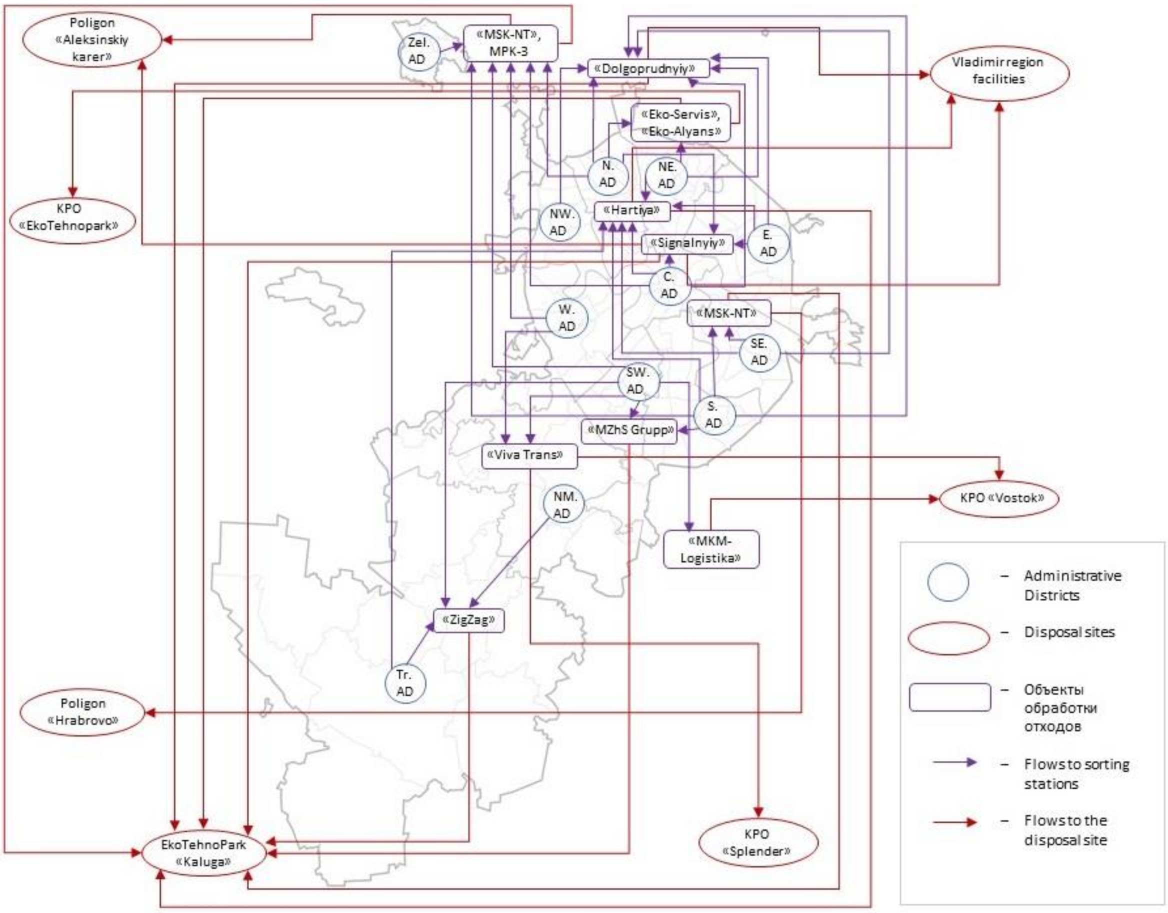
Appendix I, Figure 1 – The scheme of MSW flows directed to the final objects via transfer stations



Appendix I, Figure 2 – The scheme of MSW flows that are sent directly to final waste management facilities



Appendix I, Figure 3 – The scheme of MSW flows to the final disposal sites through waste sorting stations



Appendix II, Table 1 – Moscow waste management facilities

№	Name of the facility	Capacity, thous. tons/year	Location
Thermal waste hazard reduction (MSWI plants)			
1	LLC «EFN Ekotehprom MSZ-3»	360	Moscow
2	LLC «Hartiya», MSZ-4, Rudnevo	250	Moscow
3	MSZ «Voskresensk»[2]	350	Moscow region
4	MSZ «Noginsk»[2]	350	Moscow region
5	MSZ «Solnechnogorsk»[2]	350	Moscow region
6	MSZ «Naro-Fominsk»[2]	350	Moscow region
Waste transfer stations (TS)			
1	PRK «Nekrasovka»	500	Moscow
2	PRK «Boynya»	500	Moscow
3	«Ekotehprom», Chertanovskaya	250	Moscow
4	LLC«Hartiya», Baykalskaya	130	Moscow
Waste sorting stations (SS)			
1	LLC«Hartiya»	670	Moscow
2	LLC«Viva Trans»	490	Moscow
3	LLC«EkoLayn»	480	Moscow
4	LLC «MSK-NT», Ostapovskaya	400	Moscow
5	Ekotehprom, MPK-1 «Kotlyakovo»	375	Moscow
6	LLC "Hartiya", Rudnevo	250	Moscow
7	LLC «EkoLayn», Dolgoprudnyiy	220	Moscow region
8	LLC «ZigZag»[1]	200	Moscow
9	LLC «MZhS Grupp»[1]	200	Moscow
10	LLC «MSK-NT», MPK-3	175	Moscow

11	LLC «Eko-Servis»[1]	155	Moscow
12	LLC «MKM-Logistika»	39	Moscow region
13	LLC «Eko-Alyans»[1]	45	Moscow
14	PRK «Nekrasovka»[2]	500	Moscow
15	PRK «Boynya»[2]	500	Moscow
Sorting before the landfill			
1	EkoTehnoPark «Kaluga»	1000	Kaluga region
2	KPO «Vostok»	500	Moscow region
3	KPO «Povarovo»	500	Moscow region
4	KPO «Hrabrovo»[1]	250	Moscow region
5	KPO «Aleksinskiy karer»[1]	450	Moscow region
6	KPO «Severnyiy»	450	Moscow region
7	KPO «EkoTehnopark»[1]	350	Moscow region
8	KPO «Ozernaya»[1]	350	Moscow region
9	KPO «Don»[1]	300	Moscow region
10	KPO «Yuzhnyiy»[1]	300	Moscow region
11	KPO «Progress»[1]	350	Moscow region
Landfill			
1	EkoTehnoPark «Kaluga»	1563	Kaluga region
2	KPO «Vostok»	500	Moscow region
3	KPO «Povarovo»	500	Moscow region
4	KPO «Hrabrovo»[1]	450	Moscow region
5	KPO «Aleksinskiy karer»[1]	450	Moscow region
6	KPO «Severnyiy»	450	Moscow region
7	KPO «EkoTehnopark»[1]	350	Moscow region
8	KPO «Ozernaya»[1]	350	Moscow region

9	KPO «Don»[1]	300	Moscow region
10	KPO «Yuzhnyiy»[1]	300	Moscow region
11	KPO «Splender»	130	Moscow region
12	KPO «Progress»[1]	350	Moscow region
13	Facilities of the Vladimir region	No data available	Vladimir region
[1] are only operated in Scenario 0 [2] are operated in all scenarios except Scenario 0			

Appendix III, Table 1 - Inventory analysis data on transportation processes

Transported cargo	Route	Distance, km	Type of transport
Mixed MSW	Container site – TS «Chertanovskaya»	13	Truck, Euro 5, 12 - 14t gross weight / 9,3t payload capacity
	Container site – TS «Baykalskaya»	9	
	Container site – TS «Boynya»	17	
	Container site – TS «Nekrasovka»	25	
Mixed MSW, after TS[1]	TS «Chertanovskaya» – KPO «Don»	130	Rail transport cargo - Electric, extra-large train, gross tone weight 2000t / 1452t payload capacity
	TS «Baykalskaya» – KPO «Severnyiy»	97	
	TS «Boynya» – EkoTehnoPark «Kaluga»	205	
Mixed MSW, after TS[2]	TS «Chertanovskaya» – EkoTehnoPark «Kaluga»	184	
	TS «Baykalskaya» – EkoTehnoPark «Kaluga»	205	
Mixed MSW, after sorting and TS[2]	TS «Boynya» – EkoTehnoPark «Kaluga»	202	
Mixed MSW, after TS[1]	TS «Nekrasovka» – KPO «Vostok»	137	
	TS «Nekrasovka» – KPO «Ozernaya»	78	
	TS «Nekrasovka» – KPO «Progress»	147	
	TS «Nekrasovka» – KPO «Yuzhnyiy»	87	
Mixed MSW, after sorting and TS[2]	TS «Nekrasovka» – Facilities of the Vladimir region	136	
	TS «Nekrasovka» – KPO «Povarovo»	95	
	TS «Nekrasovka» – KPO «EkoTehnopark»	136	
Mixed and separately collected MSW	Container site – SS «Hartiya»	20	Truck, Euro 5, 12 - 14t gross weight / 9,3t payload capacity
	Container site – SS «MKM-Logistika»		
	Container site – SS EkoLayn «Signalnyiy»		
	Container site – SS « MSK-NT»		
	Container site – SS «MSK-NT MPK-3»		
	Container site – SS «Viva Trans»		

Separately collected MSW	Container site – SS «Dolgoprudnyiy» «EkoLayn»		
Mixed MSW[1]	Container site – SS «ZigZag»		
	Container site – SS «MZhS Grupp»		
	Container site – SS «Eko-Alyans», «Eko-Servis»		
Mixed MSW after sorting	SS – Facilities of the Vladimir region	150	Truck-trailer, Euro 5, 28 - 34t gross weight / 22t payload capacity
	SS – KPO «Vostok»	166	
	SS – Poligon TBO «Aleksinskiy karer»	76	
	SS – Poligon TBO «Hrabrovo»	142	
Mixed MSW after sorting[1]	SS – KPO «EkoTehnopark»	106	
	SS – EkoTehnoPark «Kaluga»	181	
Separately collected MSW after sorting	SS – Facilities of the Vladimir region	150	
	SS – EkoTehnoPark «Kaluga»	207	
	SS – KPO «Vostok»	155	
	SS – Poligon TBO «Aleksinskiy karer»	60	
	SS – Poligon TBO «Hrabrovo»	142	
Separately collected MSW after sorting[1]	SS – KPO «Splender»	175	
Mixed MSW	Container site – MSZ-4 «Hartiya», «Rudnevo»	27	Truck, Euro 5, 12 - 14t gross weight / 9,3t payload capacity
	Container site – MSZ-3 «EFN Ekotehprom»	30	
Mixed MSW[2]	Container site – MSZ «Naro-Fominsk»	62	
	Container site – MSZ «Voskresensk»	85	
	Container site – MSZ «Noginsk»	53	
	Container site – MSZ «Solnechnogorsk»	53	
Mixed MSW	Container site – KPO «Vostok»	163	Truck, Euro 5, 12 - 14t gross weight / 9,3t payload capacity
	Container site – KPO «Severnyiy»	104	
	Container site – KPO «Aleksinskiy karer»	86	
	Container site – KPO «Don»	134	
	Container site – KPO «Povarovo»	45	
	Container site – KPO «Hrabrovo»	123	

	Container site – KPO «EkoTehnopark»	104	
	Container site – EkoTehnoPark «Kaluga»	171	
Separately collected MSW	Container site – KPO «Severnyiy»	115	
	Container site – KPO «Povarovo»	77	
Biowaste[3]	Container site – Composting plant	100	Truck, Euro 5, 12 - 14t gross weight / 9,3t payload capacity
Biowaste[4]	Container site – Anaerobic digestion plant		
[1]Present only in baseline Scenario 0 [2]Appears in a scenario other than baseline Scenario 0 [3]Present only in Scenario 2.1 [4]Present only in Scenario 2.2			