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

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ABSTRACT

This study provides the first life cycle assessment (LCA) for municipal solid waste waste management system in one of the largest cities in Europe, Moscow. Its significance stems from recent important changes in the waste management system, the introduction of limited source separate collection in 2020, and the first examination of sorted municipal solid waste (MSW) composition. Moscow city generates 8.1 million tonnes of MSW per year, most of which is still mainly disposed of in landfill sites. The study assesses the current situation, the waste management system planned to be operational by 2024 and proposes improvements to separate collection and treatment of organic waste that could be adopted in the future. In this context, 6 scenarios are compared using LCA based approach. The impacts are presented as global warming potential (GWP), acidification potential (AP) and eutrophication potential (EP). The results show that the existing MSW management system has the highest GWP and AP. Planned changes to the system by 2024 will reduce impacts in all categories. The largest emissions reduction potential is found for refuse-derived fuel (RDF) production and its use in cement kilns as a replacement for coal, which reduces emissions by 1.1 kg CO_2-eq/kg_{RDF} and results in a negative AP. The change in EP remains negligible. Separate collection and treatment of biowaste is also beneficial, with anaerobic digestion being the most advantageous treatment method. Nevertheless, even after the implementation of all initiatives, landfill still represents about 53% of direct emissions in GWP. Sensitivity analysis estimated that flaring of landfill gas can reduce GWP from landfill sites by a factor greater than two. With these changes, the total emissions of the system approach zero. Energy recovery at MSW incineration plants and substitution to the grid gives reductions in GWP and EP in the range of 35% and provides especially significant reductions in AP. The waste management system in Moscow accounts for 3% of residents' carbon footprint, which might drop to 1% if appropriate changes to the system are implemented.

1. Introduction

The primary municipal solid waste (MSW) management method in developing countries or countries with economies in transition is disposal in landfill sites, and Russia is no exception. According to a governmental report, landfill of MSW accounts for 87% of total MSW generated, while only 2.2% of MSW is sent to waste hazard reduction, including MSW incineration (MSWI) without energy recovery (Ministry of Natural Resources and Environment of the Russian Federation, 2018). The remaining 10–11% MSW goes to pre-treatment at centralized sorting facilities, after which it can be partially recycled. It is worth mentioning that governmental statistics only report information for official waste management sites. It is estimated that 30 000 to 100 000 unauthorized dumps exist across the country (Volkova A.V., 2018), meaning that the share of waste landfilled and dumped will be higher than given by official statistics.

Russian and European legislation recognize landfilling as the least favorable method for waste disposal and place it at the bottom of the waste management hierarchy (European Commission, 2008; Federal Law On Production and Consumption Waste 89-FZ, 1998). Landfilling, especially if not properly managed and engineered, can cause significant environmental impacts through soil and air pollution, leading to contamination of groundwater and surface water, occupation and degradation of large areas of land, and emission of significant volumes of greenhouse gases (GHG). The impact of the latter is substantial: methane emissions contribute 73% to the total GHG emissions in the “Waste” sector (Ministry of Natural Resources and Environment of the Russian Federation, 2018). Such high volumes of methane formation at landfill sites are caused by the high percentage of organic matter in

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MSW and anaerobic conditions during its decomposition process. Except for one landfill located in the Leningrad Region (Prodex Energy, 2019), Russian landfill sites are not equipped with landfill gas collection systems. The easy availability of landfill disposal and its low cost explain the low share of secondary materials recovered from waste, despite a significant number of potential waste recycling facilities and opportunities being currently underutilized (Government Decree of the Russian Federation 84-r, 2018).

Although landfilling has long been used, waste management policy in Russia is changing significantly: new principles and rules are being proposed and adopted, and targets are being set for the development of the waste treatment sector. The fundamental degree of these changes is best reflected by the term used by the mass media – "The Garbage Reform" (Shamova and Myslyakova, 2019). These changes include implementation of two-bin source separation and waste collection system, a ban on landfilling of certain waste fractions, the introduction of territorial waste management scheme, and the appointment of regional operators who are responsible for waste management in each specific region from transportation to utilization and final disposal.

This study focuses on Moscow, the capital of the Russian Federation. Moscow is one of the most populous cities in Europe (Eurostat, 2016); as of January 1, 2020, its population reached almost 12.7 million people (Mosstat, 2020). The total area of the city is 2570 km^2. The territorial waste management scheme for Moscow (territorial'naya shema obrascheniya s othodami) was approved by the Moscow City Department of Housing, Utilities and Amenities in December 2019. According to waste reform legislation, the waste management scheme should contain comprehensive descriptions of the existing situation and planned outcomes of future changes, including data on the amount of MSW generated, treatment and disposal targets, waste collection systems, and treatment, incineration and landfilling facilities (Official website of the mayor of Moscow, 2019). The territorial waste management scheme for Moscow estimated that 8.1 million tons (Mt) of MSW would be generated in Moscow in 2020, which is 640 kg of MSW per person. To compare, MSW generation in Russia is, on average, about 420 kg per capita (Shamova and Myslyakova, 2019). The difference is explained, firstly, by a higher standard of living and greater purchasing power, and secondly, by the large number of people working in the city but actually living in the surrounding Moscow Region. On the scale of the entire country, MSW generation in Moscow accounts for 15% of MSW generated in Russia, which is around 54 Mt p.a. in total (Ministry of Natural Resources and Environment of the Russian Federation, 2018).

The development of a sustainable MSW management system is an important and complex issue. The Russian system is currently undergoing change, so it is important to use scientifically accepted methods to examine the environmental feasibility of the strategies under consideration. When choosing the most environmentally-friendly option, the entire life cycle must be taken into account (European Parliament and Council, 2008). Life cycle assessment (LCA) is a method capable of quantifying the potential environmental impacts of a solid waste management system taking into account both local and site-specific features (ISO, 2006a, 2006b). Laurent et al. (2014) emphasize that strategic decision-making should avoid utilization of generalized results from other studies and that case-specific LCA based on local conditions should be conducted.

In 2019, Russia joined the Paris Agreement and now it has become increasingly important to monitor GHGs and apply strategic planning based on reduction goals. In here, LCA can be used to quantify the emission reductions, in particular greenhouse gas emissions, of the whole MSW management system.

Only a limited number of studies have focused on the LCA of waste management systems in the Russian Federation. The majority of work has been in the form of environmental impact assessments and environmental management reports.

A pioneering LCA study was carried out by Tulohonova and Ulanova (2013) for the city of Irkutsk. This work considered the impact of an integrated MSW management system from the perspective of resource conservation and environmental, economic and social aspects. The study considered 4 scenarios and concluded that the development of recycling systems and the introduction of organics utilization has high social acceptability and results in environmental load reduction but requires substantial capital investment. Vaisman et al. (quoted in Tulohonova and Ulanova, 2013) assessed 19 MSW life cycle scenarios based on resource, environmental and economic criteria for the city of Perm. The preferred MSW management scenario included separate collection of waste, transportation of waste through transfer stations (TS), and sorting in a composting plant with recovery of recyclable materials and composting of organic matter. Kaazke et al. (2013) from the Technical Institute of Berlin analyzed 8 MSW treatment scenarios for two Russian cities: Khanty-Mansiysk and Surgut. The conclusions from the results were the same for both cities: sorting by the general population and separate treatment of different types of waste significantly increases the ecological efficiency of the MSW management system. Based on the LCA results, it was found that the best scenarios for both cities are incineration of waste, application of anaerobic mechanical biological treatment (MBT) and attainment of recycling rates around 20%. Starostina et al. (Starostina et al., 2014, 2018) conducted research focused on landfill modification and development of alternative scenarios the results of which confirmed and complemented the study of Tulohonova and Ulanova (2013).

This study aims to meet the need for scientific research and life cycle thinking in the context of the ongoing reform of the waste management system in Moscow and to address the absence of LCA studies for Moscow. Previous studies were based on assumptions and hypothetical scenarios for the implementation of separate waste collection, but this paper examines the real situation that exists now at the time of the introduction of the two-bin collection system. More importantly, a new composition of sorted MSW studied in 2020 was used, which was provided by Ecoline, a waste management operator in Moscow. Therefore, the study aims to analyze the environmental impacts of the current and proposed MSW management systems in Moscow taking into account information presented in the newly developed territorial waste management scheme. The study includes several scenarios representing possible development of the MSW management system that can be used in decision-making for further development of waste management in the city of Moscow.

2. Materials and methods

The LCA of the MSW management system in Moscow was done according to the guidelines given in ISO 14040 and ISO 14044 (ISO, 2006a, 2006b). The waste management model was created using GaBi LCA software, version 7 (Sphera, 2020), which is widely applicable worldwide (Herrmann and Moltesen, 2015).

Owing to the absence of a unified database on waste composition, waste generation rates, recycling efficiencies and waste volumes (Kaazke et al., 2013; Tulohonova and Ulanova, 2013), various data sources were used to reflect the current situation and the proposed changes. The territorial waste management scheme for the city of Moscow was used as the main source of data on the MSW management system as it is the only official resource provided by Moscow authorities. Some data about waste treatment at facilities, equipment in use and research of changes in the composition of MSW after implementation of two-bins waste collection was provided by the waste management company Ecoline LLC (2021), which operates in the Central and Northern districts of Moscow. Other necessary information was taken from Russian and European literature sources and from the GaBi (Sphera, 2020) and Ecoinvent databases (Ecoinvent, 2019).

2.1. Goal and scope

The goal of this study is to assess and compare the environmental impact of the current MSW management system in Moscow (2020) and its impact at the end of 2024 following implementation of changes proposed in the territorial waste management scheme (Official website of the mayor of Moscow, 2019). In addition to the proposed changes in the territorial scheme, the potential environmental effects of separate organic waste collection and treatment was also studied. Study of this aspect was considered necessary because of the high environmental impact of methane emissions from landfilling of organic waste fractions.

The function of the studied system is environmentally sustainable management of MSW. The functional unit of the study is 8 100 000 tons of MSW generated in the 12 administrative districts of the federal city of Moscow in 2020. The mass of MSW in 2024 was normalized to the value of the functional unit to ensure comparability and quantitative equivalence of the studied scenarios. CML 2001 (January 2016) was used for life cycle impact assessment (LCIA). Due to the limited data on the emissions from some of the processes it was decided to assess only the three following impact categories: global warming potential (GWP) over a 100-year time span, acidification potential (AP), and eutrophication potential (EP). Biogenic carbon was calculated as climate-neutral, thus not contributing to the GWP.

The MSW management system studied is a multifunctional system and it contains processes that produce co-products, such as recycling processes. To avoid allocation, substitution of virgin materials, products, and services was done by system expansion. In other words, the “avoided burden method” (Finnveden et al., 2009) was used.

2.2. Interpretation of the territorial waste management scheme in Moscow

The territory of the federal city of Moscow is divided into 12 administrative districts: Central, Northern, North-Eastern, Eastern, South-Eastern, Southern, South-Western, Western, North-Western, Zelenograd, Troitsk and Novomoskovsk. Some waste is sent, via transfer stations, by rail to waste processing complexes, and some is sorted in Moscow at 13 sorting stations and then transported by truck to landfill sites. In 2020, 10 so-called Waste Processing Complexes (WPCs) located in the Moscow region were responsible for waste treatment and disposal of Moscow city waste, one 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.

WPCs are landfills with preliminary mechanical sorting and a possibility to stabilize screened organics and produce RDF fuel. The last two options, i.e., organic treatment and RDF production, are not in common use yet but are planned to be implemented in the near future. As of 2020, there are 2 MSWI plants without energy recovery operating in Moscow: “EcoTechProm MSZ-3″ with a 360 kt/year capacity and “Khartiya” MSZ-4 in Rudnevo with 250 kt/year capacity. By 2024, Moscow waste will be sent to an additional four MSWI plants in the Moscow region: “Voskresensk”, “Noginsk”, “Solnechnogorsk”, and “Naro-Fominsk” with a 350 kt/year capacity each. A full list of facilities is given in Table J.1 in the Supplementary Material (SM). The information presented in the territorial scheme was used as a basis for the current study. The information was critically analyzed and adjustments were made to some numbers to consider possible deficiencies in the territorial scheme data, as reflected in sub-section C1. in the SM. The actual values used in this study are presented in sub-section 2.5.

2.3. System boundaries

To specify the unit processes covered by and excluded from the product system, system boundaries were defined for all scenarios studied, shown in Fig. 1. The life cycle of waste starts from its generation at a consumer of a good and service, i.e., waste collection at special container sites. This boundary implies the so-called “zero burden” approach (Ekvall et al., 2007), which was used because waste generation remains the same in all the scenarios. In this study, however, waste generation and accumulation in waste bins was excluded from the system boundaries, and the impact started with waste collection and transportation. The regional waste operator is responsible for MSW from the moment it is loaded into the waste truck, so the system is modelled from loading of mixed and separately collected MSW into waste trucks to the final disposal stage (Government Decision of the Russian Federation 1156, 2018). The system boundaries further include waste treatment and disposal, as well as unit processes from the expanded system boundary.

The system receives MSW from the 12 administrative districts of Moscow. The MSW flows can be grouped into three streams: mixed waste (MW), separately collected waste (SCW) in co-mingled recycling bins and, from the perspective of modernization of the system, a separately collected biowaste fraction. A part of the MW and SCW is sent to sorting stations within the city, the other part to the Moscow Region. Both flows are sorted, but they differ in the recovery efficiency. A part of mixed MSW is sent to incineration plants, the remaining waste is sent either through waste transfer stations on railway routes or in trucks to WPCs, where it is treated and landfilled. Biodegradable waste flow, which is only present in Scenarios 5 and 6, is sent either to composting or to anaerobic digestion plants with further composting of the resulting digestate. All secondary materials recovered from the waste are sent to recycling and manufacturing plants.

2.4. Description of the scenarios

6 scenarios were developed for analysis of the Moscow MSW management system. The mass balance of the scenarios is shown in Fig. 2. The results are shown as percent relative to the mass of MSW which was given as 100%. The baseline Scenario 1 reflects the current situation as of 2020 and is based on data presented in the territorial waste management Scheme 79.4% of MSW is collected as mixed waste and 20.6% ends up in a co-mingled bin for recyclables. However, based on EcoLine's research, the quality of waste separation by the public varies greatly, and in Scenario 1, it is assumed that 50% of the bin for recyclables is mixed waste. About 80% of waste is landfilled, 7.4% is incinerated, and a little over 12% is modelled to be recycled.

Scenario 2 simulates the system taking into account changes which, according to the territorial scheme, will occur by 2024. The territorial waste management scheme estimates an increase in the volume of collected recyclables to 24.2%, and it is assumed that the quality of sorting has improved considerably, and mixed waste accounts for only 17% of the co-mingled bin. New incineration capacities of 1.4 Mt/year are also introduced, and as a result of these factors, the landfill share is reduced by almost 18%.

Scenario 3 and 4 are based on Scenario 2 and differ only by the integration of composting of screened organics at WPCs in Scenario 3 and the production of RDF in Scenario 4. From the mass previously sent to landfill, 5.2% of MSW is composted to stabilize the organics before use in the landfill, and 9.3% of MSW is processed into RDF fuel.

Scenarios 5 and 6 are alternative scenarios that are not based on the territorial scheme. They simulate a more optimal MSW management system from a global warming perspective (Boldrin et al., 2009; Dawn Stretton-Maycock and Graham Merrington, 2009; Kaazke et al., 2013) that relies on the separate collection of biowaste from mixed MSW with a 30% collection rate. In Scenario 5, composting with compost as a useful product is chosen as a treatment method. In Scenario 6, organic waste is sent to an anaerobic digestion plant to produce biogas and digestate, which is then composted and consumed. The energy from burning biogas is converted to electrical energy. Because of the separate collection of organics, all shares of final disposal are reduced.

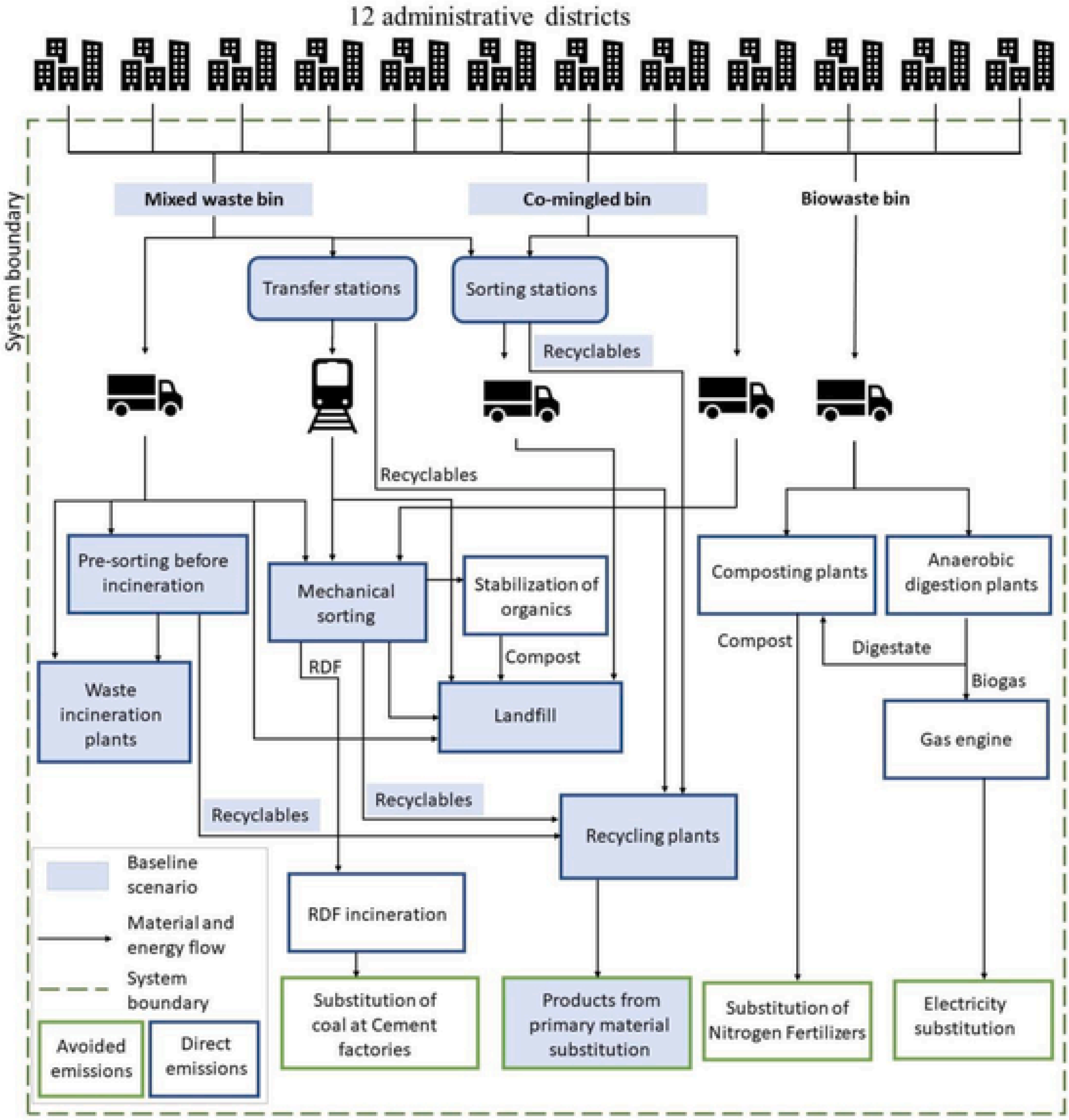

Fig. 1. Systemic boundaries of the study.

2.5. *Life cycle inventory analysis*

2.5.1. *Waste composition*

The introduction of a two-bin waste collection system, i.e. co-mingled and mixed waste containers, started at the beginning of 2020 (Rudnitsky, 2020), and full implementation should be completed by January 1, 2022 (Federal Law On Production and Consumption Waste 89-FZ, 1998). 18 000 container sites will be located in front of multi-apartment buildings, 95% of which are equipped for separate waste collection. The number of container sites in more rural areas with private houses is about 19 200, but only 33% of them have 2 bins for waste separation. Appendix A of Supplementary Material presents the composition of the MSW, which is based on the composition of MSW in Moscow in 2015 (Sotnezov et al., 2015), and specific capture rates and rates of separate collection.

2.5.2. *Waste transportation*

Various modes of transportation were modelled to reflect the studied waste management system. Transportation modes and average transportation distances are shown in Table B1 of Supplementary Material for all transport flows. SCW is transported separately from mixed waste. A truck with a small payload capacity is used for in-city transportation to waste sorting and transfer stations. The sorted waste is compressed and then transported by large-capacity semi-trailer truck. This method of transport for long distances is more appropriate from both an environmental and economic point of view. However, the territorial scheme includes some waste flows from Moscow to disposal sites without waste processing and transfer to large-capacity transport; this transportation is modelled using small-capacity trucks. The third method of transportation used in the model is rail transport, which is used to transport MSW from TS to WPCs.

2.5.3. *Waste sorting*

Sorting of both MW and SCW is carried out at 11 individual waste sorting stations, 11 WPCs before landfilling and 2 sorting lines before incineration, which are listed in Table J.1 of Supplementary Material. It is planned to introduce sorting at two TS by 2024: “Nekrasovka” and “Boynia”. There is no information about the difference in the equipment at each particular sorting station, but based on data published on the official web sites of the waste management companies (Hartiya, 2017; MSK-, 2020; MZhS Group, 2020; RazDel'ny`j sbor, 2019; Viva Trans, 2017), it is concluded that sorting is mainly manual. In the WPCs, only presorting is done manually, and waste then enters a well-

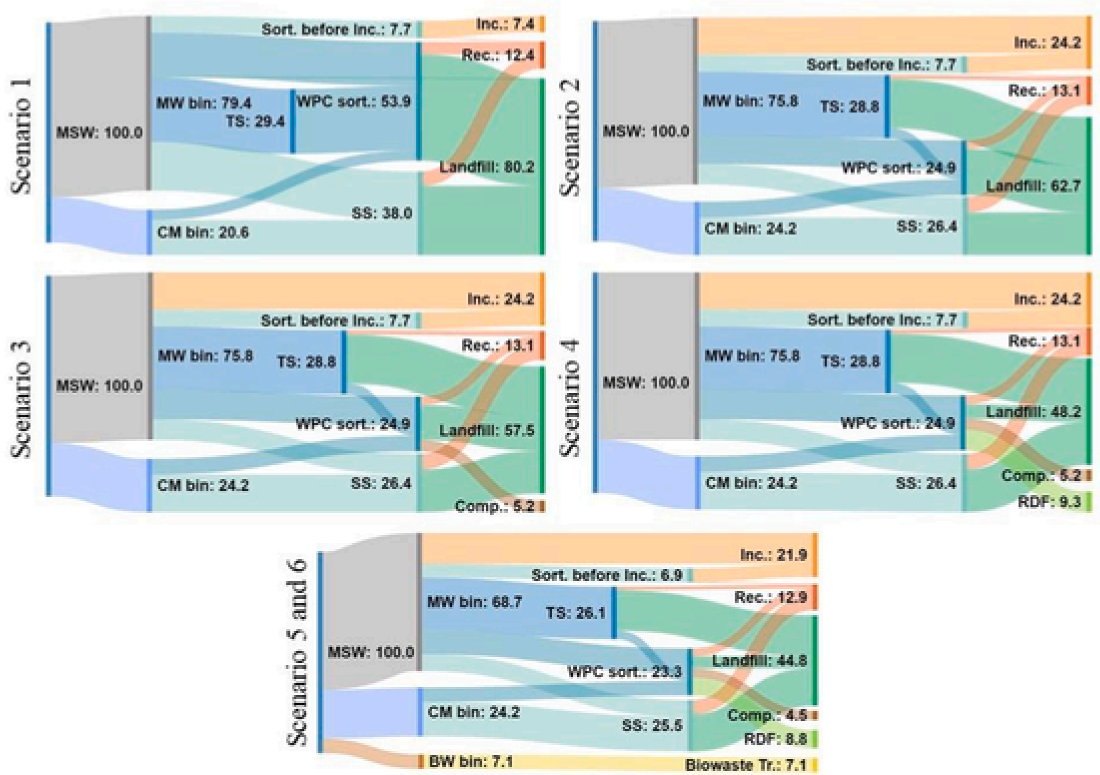

Fig. 2. –Mass balance of the scenarios, % of the total mass of MSW. MW bin – mixed waste bin; CM bin – co-mingled bin; BW bin – biowaste bin; Sort. before Inc. – sorting before incineration; Inc. – incineration; TS – Transfer Station; WPC sort. – sorting at WPC; SS – Sorting Station; Rec. – recycling; Comp. – composting after sorting at WPC; RDF – production of RDF at WPC; Biowaste tr. – treatment of separately collected biowaste.

equipped sorting line that includes a trommel screen, optical separator for plastics, and a ballistic and magnetic separator (EcoLine LLC, 2021). Calculation of recovery efficiencies is shown in Appendix C of Supplementary Material.

2.5.4. *Composting at WPCs*

The fine fraction from screening is modelled to be biologically treated at all WPCs, but the implementation of this technology only began in 2020. Enclosed windrow composting in an aerated pile is modelled in Scenarios 3–6 according to Boldrin et al. (2009). Life cycle impact (LCI) data is summarized in Appendix D of the Supplementary Material. The compost product is used as a cover layer between the layers in the landfill, where it substitutes an equivalent volume of soil that would otherwise be excavated for the same purpose.

2.5.5. *Incineration of RDF*

In Russia, RDF is currently produced only in small quantities and it is purchased by single plants. However, WPCs are planning to start producing RDF in the coming years (EcoLine LLC, 2021). The studies of Havukainen et al. (2017), Nasrullah et al. (2015) and Montejo et al. (2013, 2011) were utilized in modelling the RDF production process. RDF production and RDF combustion in a cement kiln as a replacement for hard coal was modelled in Scenarios 4–6. The RDF production process, its inventory data and the inventory of the impact from RDF and coal incineration are presented in Appendix E of the Supplementary Materials.

2.5.6. *Landfilling*

In the 2020 baseline scenario, waste disposal is carried out at 12 WPCs: 11 are located in the Moscow region and 1 in the Kaluga region. In addition, there is one landfill site in the Vladimir region. The formation of landfill gas (LFG) and emissions from the landfilling were modelled using the IPCC default method (IPCC, 2006). The values used in the IPCC model as well as the inventory of the landfills are presented in Appendix F of Supplementary Material. There is no landfill gas collection system or flaring at any of the landfills in use which is a common practice in Russia.

2.5.7. *Mixed waste incineration*

Only MW is intended for incineration. The two MSWI plants currently operating in Moscow (Scenario 1) have pre-sorting, but due to the absence of information on pre-sorting at the four new MSWI plants (Scenarios 2–6) in the territorial scheme, it is assumed that mixed MSW will go straight to incineration without pre-sorting. As with landfill disposal, incineration is modelled separately for different waste fractions to take into account the composition of MSW in Moscow. MSWI provides energy for the needs of the MSWI plant, but the energy is not currently used in the grid, so no energy substitution is modelled from waste incineration. The unit processes used to model waste incineration are listed in Table G.1 of the Supplementary Material.

2.5.8. *Biowaste treatment*

Individual facilities for organic treatment are only present in Scenarios 5 and 6, where biowaste is collected separately. In Scenario 5, a windrow composting process “AT: Open windrow composting (incl. compost application and crediting) BOKU” (Sphera, 2020) is used. Emissions from the utilization of compost as a product, as well as avoided emissions, are included in the process. In Scenario 6, biowaste is treated by anaerobic digestion (AD). The digestate is sent for composting and the biogas is directed to a gas engine to generate electricity with an efficiency of 37%. The biogas purification process is not included in this study. The data for AD is modelled using “Treatment of biowaste by anaerobic digestion, Switzerland” and biogas incineration using “Heat and power co-generation, biogas, gas engine, Germany” from the Ecoinvent database (Ecoinvent, 2019). The substitution process for electricity generated is «RU: Electricity grid mix 1kV–60kV».

2.5.9. Materials recycling

Recycling processes manufacture products that can potentially substitute primary products on the market. The efficacy of recycled materials to substitute primary products, or the so-called substitution ratio, depends on the material recovery efficiency and the ability of the market to accept a secondary product of potentially lower quality, i.e., the market ratio. In this study, the substitution ratios which take into account the recovery efficiency and the market ratio as described by Andreasi Bassi et al. (2017) were used as follows: steel – 84%, aluminum – 93%, glass – 100%, PET – 61%, HDPE – 73%, paper and cardboard – 83%.

Modelling of recycling processes can cause significant uncertainties in LCA results (Brogaard et al., 2014) as processes vary from country to country. In the absence of information on specific recycling processes in Russia, the processes mentioned in Table H.1 of Supplementary Materials were used. An assumption is also made that a secondary product replaces only one type of other product on the market. For example, the PET bottle-to-bottle recycling approach is applied in one plant in Russia, which is located in the Moscow region (Plarus, 2021), but there are others that use recycled PET to produce food packaging (EcoTechnologies, 2021).

2.6. Sensitivity analysis

Sensitivity analysis was performed to verify the reliability of the obtained results. Two parameters that could be implemented in the waste management system in the coming years were checked, namely, landfill gas flaring and energy recovery at MSWI plants by connection to the electricity grid and district heating networks.

2.6.1. LFG flaring

LFG is collected at engineered landfills and collection efficiency can reach 60–85% (SCS Engineers, 2008). A 60% collection rate is considered in the sensitivity analysis of this study. The resulting emissions were calculated taking into account flaring efficiency of 90% (UNFCCC, 2006). Appendix I of Supplementary Materials presents the calculation of emissions during flaring.

2.6.2. Energy recovery from MSWI

Russian waste management policy currently focuses on development of waste incineration. The State Atomic Energy Corporation “Rosatom”, which is the operator of industrial waste management of hazardous waste classes I and II, has announced plans to build 25 new incinerator plants with energy recovery (ROSATOM Corporation, 2020). Thus, it is relevant to analyze the environmental impacts if the plants supply the power grid and provide heat energy to consumers. The names of the used processes and their efficiencies are shown in Table G.1. in the SM. The avoided emissions are based on the substitution of energy from the following energy sources: “RU: Electricity grid mix 1kV–60kV”, and “RU: Process steam from natural gas 90%” (Sphera, 2020). Shares of energy sources in Russia as a percentage of gross energy production: 47.4 natural gas, 18.6 nuclear, 17.1 hydro, 8.3 hard coal, 7.0 lignite, 0.6 fuel oil, 0.6 coal gases, and the rest is waste-to-energy, photovoltaics, geothermal, wind, biomass and peat.

3. Results and discussion

3.1. Contribution analysis

The results of the study are grouped into specific process categories and presented in Figs. 3–6. The numerical results are presented in Appendix K of Supplementary Materials for more precise results analysis. It can be seen that the existing waste management system presented in Scenario 1 has the highest impact on climate change of 4057 kt CO_2-eq or 0.5 t CO_2-eq per 1 t of waste generated. Direct emissions from landfills without LFG collection in Scenario 1 generate 0.65 t CO_2-eq per 1 t of waste, thus contributing 76% to the total positive impact. In another LCA study in Russia (Kaazke et al. (2013), emissions from landfill were given as 0.25 t CO_2-eq./t_{MSW}; however, the landfills were operated in a Siberian climate, which would be expected to generate less LFG. GHG emissions from landfills operating in Rome were 1.31 t CO_2-eq/t_{MSW} (Cherubini et al., 2009), which were higher due to a higher content of methane in the LFG (58% vs 50% in our study) and higher content of biowaste (50% vs. 24% in our study). Similar findings were observed in the study by Erses Yay (2015) for the Turkish conditions, where landfill sites without gas collection system were found to emit 1.84 t CO_2-eq./$t_{MSW.}$ Thus, it can be seen that although landfill emissions vary considerably, their impact on climate change is consistently high.

The biggest structural changes in the waste management system are found during the shift from Scenario 1 to Scenario 2, which represents the Moscow waste management in 2024 after planned changes have been implemented. The share of waste that is landfilled decreases by 17.5%, mainly due to increased MSWI. However, the amount of all materials recycled, except for plastics, decreases slightly. This reduction in recycling occurs because there is no sorting of waste before incineration in the new MSWI plants and, thus, waste which was separated from the mixed waste flow before landfilling in Scenario 1 is now incinerated in Scenario 2. As regards plastics, its recycling rate increases since there are higher efficiencies of waste sorting by the general population, and plastics represent the major share of source-separated waste in Scenario 2, as found in recent studies on waste composition in Moscow (EcoLine LLC, 2020). As a result, the total GWP in Scenario 2 drops by only 21%.

In Scenario 3, there is a new MBT composting process in the WPCs with a rather low-quality output and this results in a further 7% reduction of GWP. The optimal implementation of changes in the planned MSW management system is modelled in Scenario 4 with the introduction of production of RDF, which can be used to substitute coal. This measure reduces the total GWP of the system by almost 50% compared to Scenario 3. Two options for RDF production were considered: from mixed waste and from separately collected waste. RDF from SCW had a higher LHV of 18.5 MJ/kg_{RDF} compared to the LHV of RDF from MW, which was 12 MJ/kg_{RDF}. Because both waste flows were present in the system studied in Scenario 4, the weighted average LHV of RDF produced was 13.8 MJ/kg. To substitute 1 kg of coal, 1.2 kg of RDF from SCW or 1.9 kg from MW is required. The use of RDF in a cement kiln resulted in avoided emissions of 1.1 kg CO_2-eq/kg_{RDF} when considering direct emissions from RDF incineration and avoided emissions from coal combustion. The value is smaller than the value published in the European Commission report (Gendebien et al., 2003) of 1.6 CO_2-eq/kg_{RDF}. It should be noted that the model used in this study considered that only 9.3% of the waste generated would become RDG, which is about 750 kt/y. Currently, only one cement factory in Russia publicly reports the use of RDF (LafargeHolcim, 2020), so new initiatives for RDF incineration would be needed.

In Scenarios 5 and 6, implementation of separate collection of 30% of biowaste from mixed waste further reduces the GHG emissions by 20% and 23%, respectively, compared to Scenario 4. Finally, the lowest impact on climate change is observed in Scenario 6, where all planned changes are implemented along with separate collection of biowaste followed by anaerobic digestion. However, it is seen that even after all the changes are implemented, landfilling has the highest impact on the results, contributing 53% to the total positive impact of the system. In the context of the capture rates used in the study and plastics recycling, the production of RDF to substitute coal showed the greatest potential for impact avoidance in the system.

The current MSW management system modelled in Scenario 1 has the highest AP of 0.08 kg SO_2-eq./$t_{MSW,}$ which is within the values

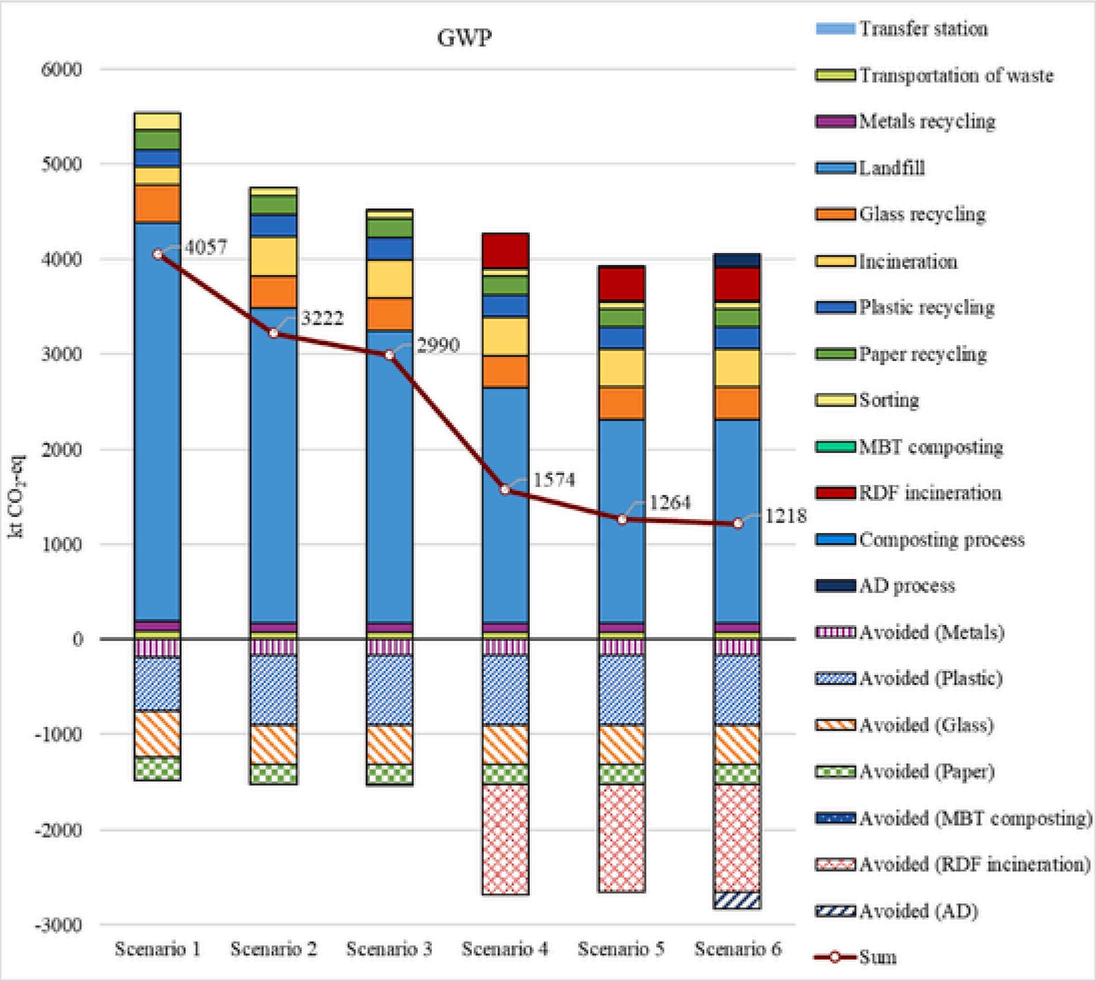

Fig. 3. Global warming potential for simulated scenarios of the MSW management system of the federal city of Moscow.

stated in literature (Cherubini et al., 2009; Erses Yay, 2015; Kaazke et al., 2013; Liikanen et al., 2018). The results of the AP vary greatly in the scenarios dominated by waste landfilling The variation is significantly higher than in the case of GWP because of a less pronounced impact of landfilling and a higher importance of other processes, such as recycling and incineration, which are present in Scneario 1. As can be seen in Fig. 4, the impact does not decrease significantly in Scenarios 2–3. In Scenario 4, however, emissions are significantly reduced and the total AP of the system becomes negative with RDF production, where the AP reduction potential is 0.61 kg SO_2-eq./t_{RDF}, which is close to the values of 0.4–0.5 kg SO_2-eq./t_{RDF} obtained by Liikanen et al. (2018). This reduction is primarily caused by avoided sulphur dioxide emissions from coal combustion which usually is rich in sulphur (Dinca et al., 2010). The value for avoided AP of coal combustion in a cement kiln used in this study is 8.7 kg SO_2-eq./t_{coal}, while the direct AP of RDF combustion is 4.76 kg SO_2-eq./t_{RDF} The actual value of the AP will, however, depend on the sulphur content of the RDF.

The treatment of organic waste at WPCs results in slight increases in AP, but the introduction of separate collection of biowaste and its treatment in individual facilities generates lower total system emissions due to avoidance of incineration and landfilling of organics, as well as some reduction in electricity consumption at the sorting stations due to lower waste sorting mass. The largest reductions in AP are observed when using anaerobic digestion as a treatment option and substitution of electricity from the grid. Other studies also mention AD as the most favored treatment method (Arafat et al., 2015; Liikanen et al., 2018).

The eutrophication results are shown in Fig. 5. As can be seen, there is no clear trend of difference between the scenarios studied. The results show that when switching from the existing system modelled in Scenario 1 to the proposed changes in Scenarios 2 and 3, the impact on EP increases slightly. This increase is because the reduction in the volume of waste landfilled has almost no effect on this impact category, whereas the higher share of waste incineration increases direct emissions if there is no energy recovery and substitution from waste incineration. Additionally, the recycling of plastics increases in Scenario 2 due to better sorting of this fraction by the general public. However, the avoided impact on EP from substitution of plastic production is lower than the direct emissions from plastics recycling, and the cumulative impact on EP is thus positive. The higher impact from plastics recycling compared to virgin production can be expected due to the use of water in the pretreatment process and washing chemicals, thus generating wastewater, which affects the EP.

The transition from Scenario 3 to Scenario 4 reduces the EP by 19% following the implementation of RDF production. RDF combustion has low values for both AP and EP. The EP reduction potential in Scenario 4 is 0.1 kg PO_4-eq./t_{RDF}, which is somewhat optimistic compared to other studies (Gendebien et al., 2003; Georgiopoulou and Lyberatos, 2018), where NO_x emissions from coal and RDF do not differ as much. Scenario 6 with anaerobic digestion has a slightly higher EP compared to composting. In all scenarios studied, the impact from both paper production and recycling makes the largest contributions to EP due to the volume of wastewater and added chemicals.

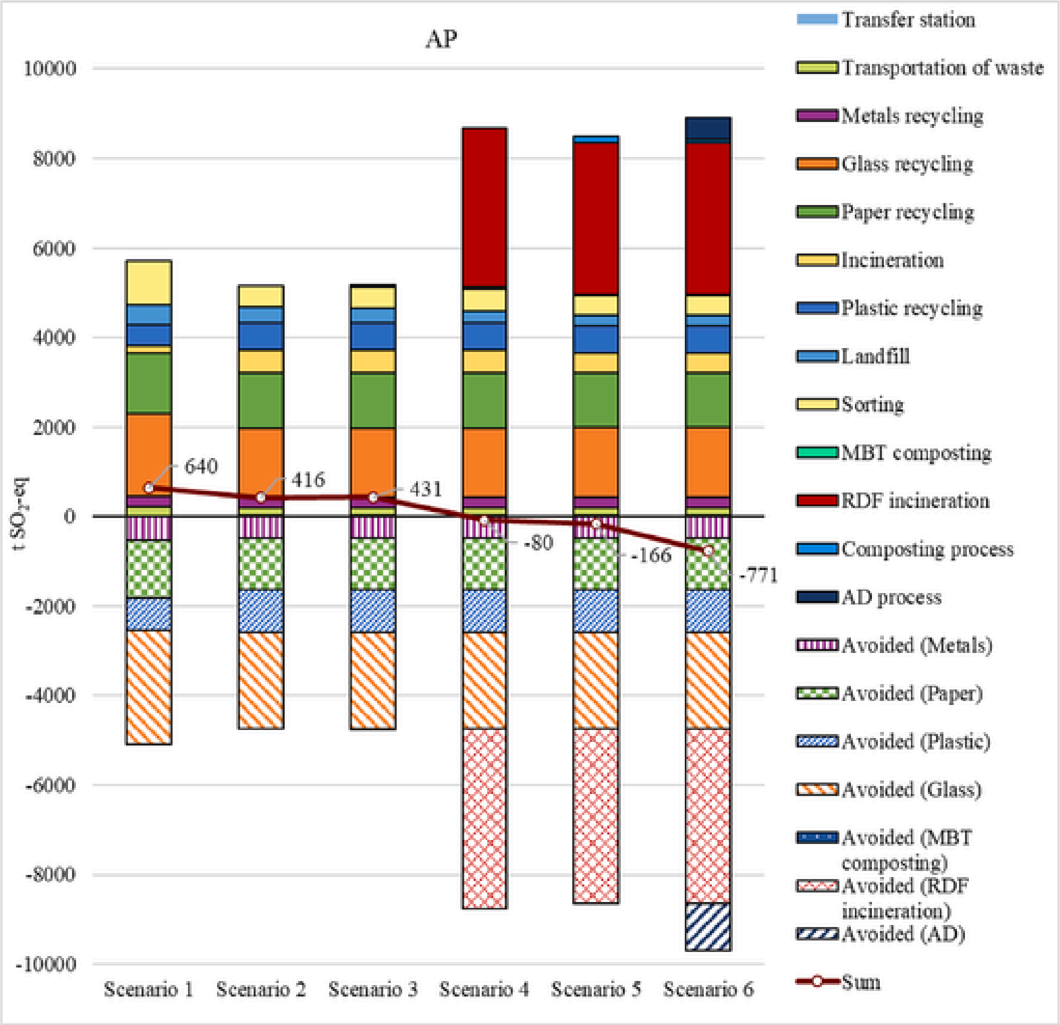

Fig. 4. Acidification potential for simulated scenarios of the MSW management system of the federal city of Moscow.

3.2. *Sensitivity analysis results*

The results of two sensitivity analyses are shown in Fig. 6. More detailed results are given in Appendix L of the Supplementary Material.

3.2.1. *Landfill gas flaring*

The implementation of an LFG flaring system has the potential to reduce greenhouse gas emissions from landfills by 54%. Since the total system emissions depend on many processes, changes in landfill emissions could reduce total emissions in each scenario by 56–95%. Potentially, in Scenario 6, the sum of the system avoided and direct emissions can fall to zero.

LFG flaring brings minor changes in the AP results. Landfill emissions are increased by 1.4% due to the formation of sulphur dioxide in the combustion process. The hydrogen sulfide contained in landfill gas does not make a significant contribution to the acidification category, but it increases the acidification potential when flared. Total system AP increases in the range of 1–4%. The simulated flaring process does not contribute to the eutrophication category as no substances causing eutrophication are produced during combustion.

3.2.2. *Energy recovery at waste incineration plants*

Fig. 6 shows changes in GWP, AP and EP for the total emissions of the waste management system for the six scenarios studied. When energy is recovered at a MSWI plant, the avoided emissions are higher than the direct emissions, so the plant emissions take negative values. Thus, the greenhouse gases from the total system are reduced by 4.5–36%. The reason for this wide range is that the scenarios take into account the composition of the incinerated waste and its energy capacity. Since these parameters vary in the different scenarios, the energy output also differs.

Energy recovery has the greatest influence on change in acidification potential. There is a strong reduction of AP when energy from the grid is substituted by energy from a MSWI plant. In this case, the avoided emissions are significantly higher than the direct emissions. This result can be explained by the fact that the combustion of fossil fuels, especially coal, produces a large amount of sulphur oxides (Dinca et al., 2010). Sensitivity analysis shows a 90–1850% reduction in the AP emissions of the total system depending on the scenario.

Eutrophication potential is considerably reduced when MSWI supplies energy to the grid, because the prevention of nitrate and nitrous oxide emissions occurs at different life cycle stages of fossil fuels (Dinca et al., 2010). The results of the sensitivity analysis indicate a reduction of total system EP emissions by 14–40% depending on the scenario.

3.3. *Person equivalents of GWP*

According to the biennial report (Ministry of Natural Resources and Environment of the Russian Federation, 2019), 1578 Mt of CO_2-eq. were emitted in Russia in 2017. In 2017, the population of Russia was 144.5 million people (The World Bank Group, 2020), and thus the carbon footprint of each citizen was 10.9 tons of CO_2-eq. In com-

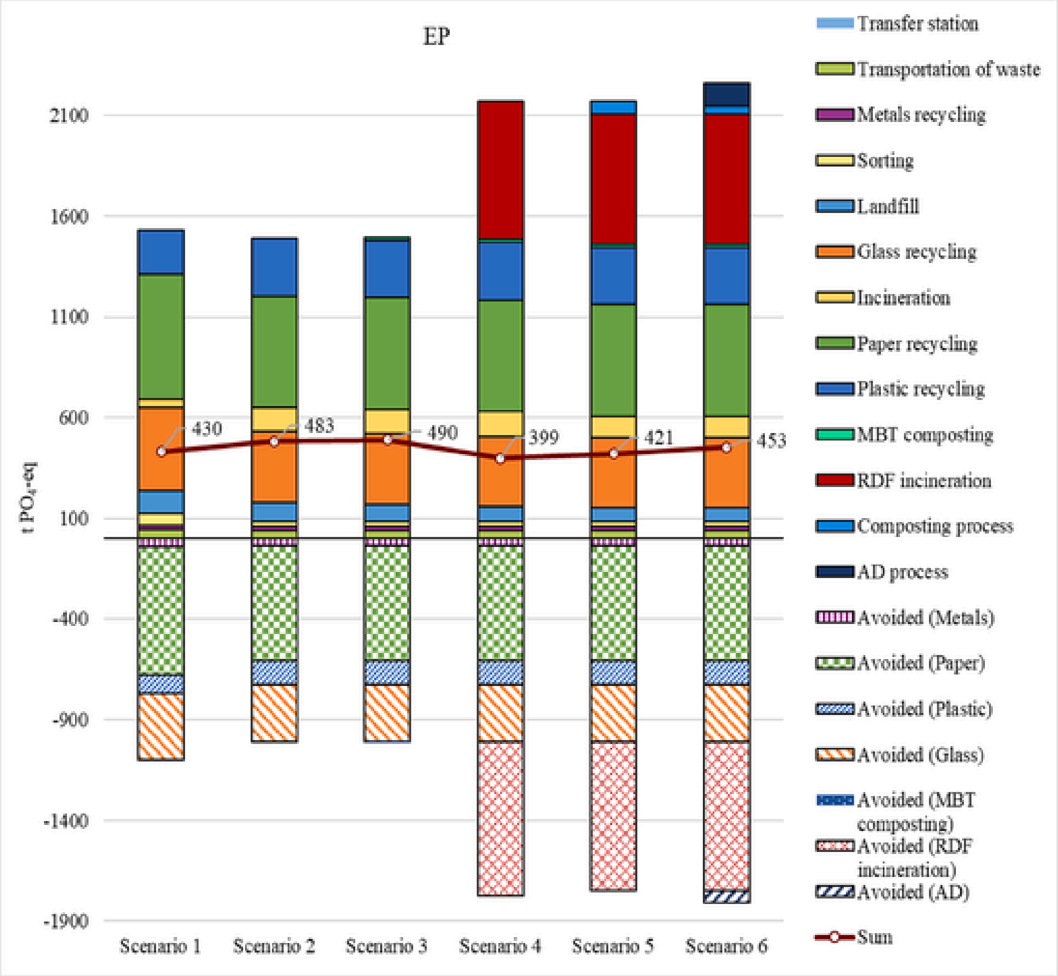

Fig. 5. Eutrophication potential for simulated scenarios of MSW management system of the federal city of Moscow.

parison, the carbon footprint of a resident in Finland is 10.4 t CO_2-eq/a, in China is 4.2 t CO_2-eq/a, and in Brazil is 2.8 t CO_2-eq/a (Akenji et al., 2019). To fulfil the objectives of the Paris Agreement (United Nations, 2015), a carbon footprint of 2.5 t CO_2-eq. per person should be achieved by 2030 (Akenji et al., 2019).

Knowing that the population of Moscow is 12.7 million people and the GWP of the existing MSW management system as of 2020 is 4057 kt CO2-eq., the impact from waste management is 320 kg CO_2-eq per Moscow citizen or 2.9% of the total carbon footprint, if the per capita carbon footprint is the same throughout Russia. A reduction from 4057 kt CO_2-eq (current scenario) to 1095 kt CO_2-eq. (best case scenario – Scenario 6) would save 230 kg of CO_2-eq. per person, which is equivalent to driving a passenger car for 1770 km, if 130 g CO_2 is emitted per km, which is the Euro-6 standard requirement.

3.4. Limitations and recommendations

A number of factors need to be borne in mind when considering the results of the LCA of the waste management system. Firstly, it should be noted that two databases (GaBi and Ecoinvent) were used due to the complexity of the studied system and the large number of unit processes involved. However, it is known that there are some discrepancies between the results of these databases (Kalverkamp et al., 2020). Nevertheless, it was estimated that the quality of the data available in the databases is higher than data modelled using secondary data from literature. This is because the data in databases often stems from primary data and is reviewed prior to the publication in the databases. Secondly, a number of assumptions were made for parameters that are not clearly described in plans for changes to the waste management system. Currently, there is no unified statistical database on waste management in Russia, and consequently, there is a lack of accurate data on the amount and type of recycled materials. The baseline scenario used targets given in the territorial waste management scheme for Moscow. However, the waste sorting efficiencies in this document were considered to be overestimated, and secondary data were thus used in the model, taking into account the experience of a waste management operator in Moscow. Thirdly, the choice of recycling processes, substitution rates and landfill modelling were also based on secondary data. The geographical representation was carried out to the closest extent possible, yet the processes were not directly representative of Russia, partly due to the low level of awareness of the LCA method in Russia. Waste composition in Moscow after implementation of the two-bin waste collection system is expected to change over time, but the exact changes are not known before the system is implemented. Consequently, estimations of the waste composition were used in the study. The issue of waste prevention and reuse is not covered in this study. The impact assessment is limited to only three impact categories. Despite the above-mentioned limitations, the study provides a clear indication of the development of the MSW management system and steps to be taken towards more environmentally sustainable waste management in Moscow. Furthermore, the scale of the potential for reduction of the environmental impact of MSW becomes clear.

Future research should investigate waste composition after the introduction of the planned waste separation and collection system, which would allow the use of up-to-date and accurate information. It would also be relevant to study in more detail the impact of the increas-

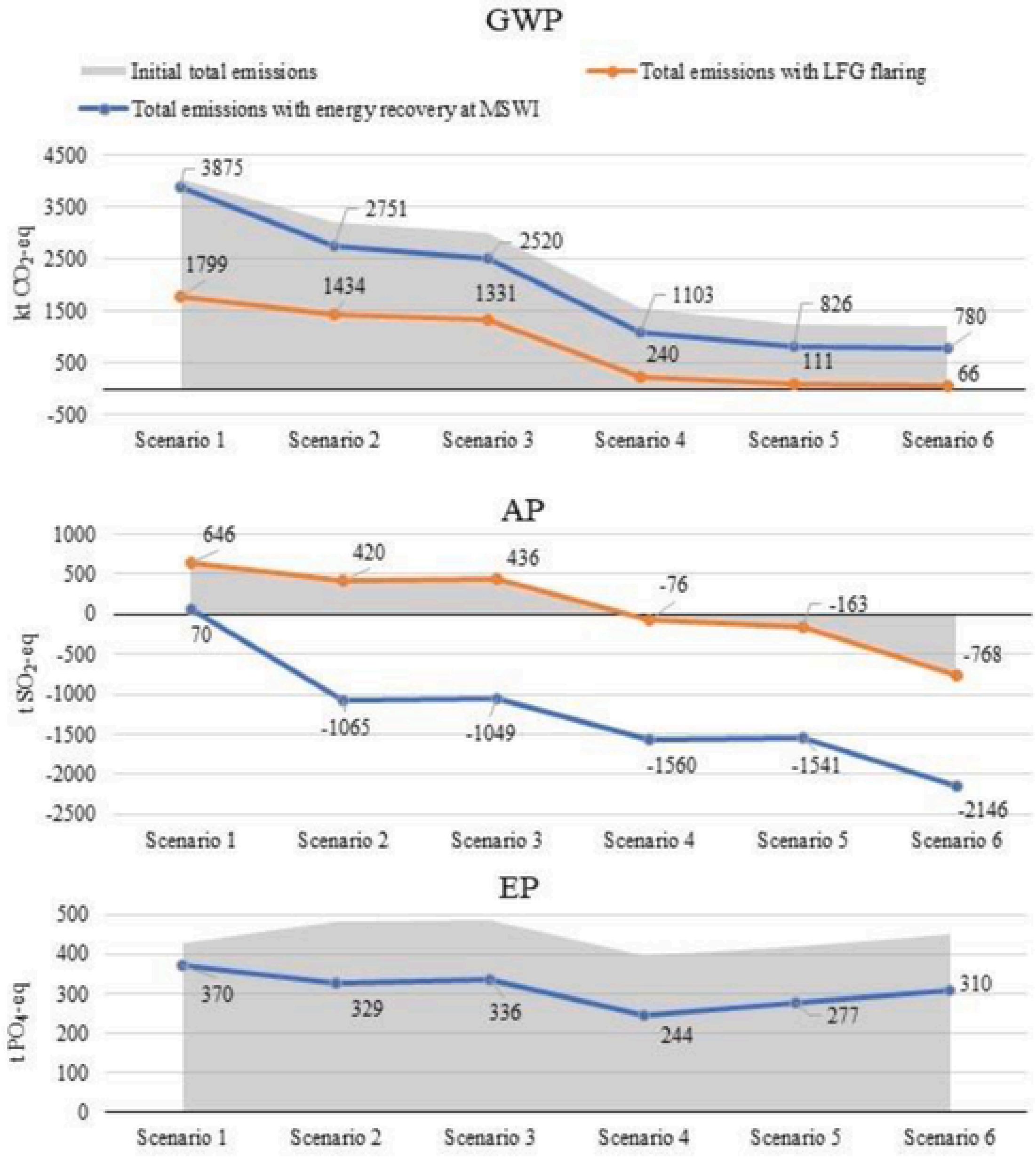

Fig. 6. – Sensitivity analysis results for LFG flaring at landfills and energy recovery at MSWI plants.

ing share of incineration over the long-term as the construction in Russia of 25 MSWI plants is currently under consideration (ROSATOM Corporation, 2020). At the end of 2019, energy recovery at MSWI became legally equivalent to renewable energy sources (Federal Law On Production and Consumption Waste 89-FZ, 1998). Yet, there is strong public resistance to such a policy. The main arguments are the danger of toxic emissions and the absence of the promotion of recycling and the development of a separate waste collection system. For this reason, a more comprehensive long-term analysis is needed to confirm the most sustainable solution.

4. Conclusions

The results of the study show that the current MSW management system (Scenario 1) generates the greatest emissions affecting climate change and acidification potential. Changes in the system planned for implementation by 2024 have the potential to reduce environmental impacts in all studied impact categories. The largest reduction potential is in Scenario 4 with RDF production, which can reduce GWP from the 500 kg CO_2-eq/t_{MSW} found in Scenario 1–194 kg CO_2-eq/t_{MSW} and reverse the AP from positive to negative. However, the change in eutrophication potential remains relatively small. Separate collection of biowaste and its treatment with anaerobic digestion also offers benefits as an advantageous treatment method, as modelled in Scenario 6.

It should be noted that even after implementation of all initiatives, landfill still contributes approximately 53% to direct GWP values. Sensitivity analysis showed that LFG flaring would reduce GWP from landfill by a factor greater than two, but it would have little effect on the other two categories. With such changes, the system has the potential to reduce the sum of its avoided and direct emissions to zero. On the other hand, energy recovery from MSWI and substitution to the grid shows GWP and EP reductions in the range of 35% and a particularly significant reduction of AP. The current solid waste management system accounts for 3% of the per capita carbon footprint of Moscow residents. However, the per capita carbon footprint from waste could drop to 1% of the total carbon footprint if the considered system changes are implemented.

Uncited reference

Ministry of Natural Resources and Environment of the Russian Federation, 2019.

CRediT authorship contribution statement

Natalia Vinitskaia: Conceptualization, Software, Investigation, Data curation, Writing – original draft, Visualization. **Anna Zaikova:** Methodology. **Ivan Deviatkin:** Validation, Writing – review & editing, Supervision. **Oksana Bachina:** Resources. **Mika Horttanainen:** Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.129407.

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