Article

Design of an Optimal Waste Utilization System: A Case Study in St. Petersburg, Russia

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Abstract: Storing municipal solid waste (MSW) in landfills is the oldest and still the primary waste management strategy in many countries. Russia is the third largest methane (CH_4) emitter country after USA and China, representing 5% of total global CH_4 emissions from waste landfilling. Due to high economical growth, the amount of waste generated in Russia has risen sharply over the last ten years. However, waste management in Russia is mainly based on landfilling. In order to design an optimal MSW utilization system considering various aspects related to sustainable MSW management, a linear programming model was introduced for this research. The performance of the proposed MSW utilization system in the target area has been evaluated in light of energy, economic, and environmental (3Es) aspects, such as system net cost, annual energy generated from the waste, and the carbon dioxide (CO_2) emissions of the system. St. Petersburg city was considered as the target area for the present analysis. The results show that the introduction of the proposed MSW system with energy recovery from waste along with a high level of material recovery has energy, environmental and economic benefits compared to the conventional treatment system. This paper emphasizes the importance of introducing waste treatment methods as an alternative to landfilling, and to improve recycling activities in Russia.

Keywords: sustainable waste management; municipal solid waste; waste-to-energy; system design; optimization; linear programming; Russia; St. Petersburg

Nomenclature

a	: waste availability coefficient (%)
b	: by-product generated in treatment facility (t/year or GWh/year)
c	: composted materials
C_{cap}	: capital cost of treatment facility (USD/t capacity/day)
cap_{tr}	: truck load capacity (t)
C_{om}	: operation and maintenance cost of treatment facility (USD/t)
CRF	: capital recovery factor
C_{tr}	: transportation cost (USD/t/km)
d	: round trip distance to treatment facility (km)
dr	: residue's round trip distance from treatment facility to landfill (km)
e	: energy carrier generated from waste
eff_{coll}	: gas collection efficiency (%)
emf	: emissions factor for treatment facility (tons of CO_2-eq./t)
em_{tr}	: emissions factor for transportation (tons of CO_2-eq./km)
gas_{gr}	: biogas generation rate (m^3/t)
i	: type of waste material
j	: type of treatment facility
k	: type of by-product
LF	: country location cost factor
LFG_{gr}	: landfill gas generation rate (m^3/t)
LHV	: lower heating value (MJ/kg)
LHV_{gas}	: lower heating value for biogas (MJ/m^3)
LHV_{LFG}	: lower heating value for landfill gas (MJ/m^3)
LHV_{RDF}	: lower heating value for RDF (MJ/t)
m	: recycled materials
nc_j	: net costs of each treatment facility (USD/year)
p	: unit price of by-product (USD/t or USD/GWh)
q	: waste material allocated to treatment facility (t/year)
fr	: fraction of residue production at treatment facility
fr_{LFD}	: fraction of materials (waste and residues) allocated for landfill disposal
fr_{WTE}	: fraction of waste allocated for energy production
fr_{WTR}	: fraction of waste allocated for recycling
T_{cap}	: planned capacity of treatment facility (t/year)
tc_j	: total cost of each treatment facility (USD/year)
T_{ot}	: treatment facility operation time (day/year)
$\eta_{e,h}$	: conversion efficiency (electricity, heat; %)

1. Introduction

Generation of municipal solid wastes (MSWs) is closely linked to the population growth process, the urbanization rate, change of lifestyle, and an increase in household income [1]. MSW contains various types of organic materials that produce a variety of gaseous products, including GHGs, when dumped, compacted, and covered in landfills. However, storing MSW in landfills is the oldest and still the primary waste management strategy in many countries. Landfills generate methane (CH_4) in combination with other landfill gases (LFGs) through the natural process of bacterial decomposition of organic waste under anaerobic conditions. Given that CH_4 is about 21 times a more powerful greenhouse gas (GHG) than carbon dioxide (CO_2), emissions of LFGs are an important source of GHGs. Worldwide CH_4 emitted from landfilling of MSW accounted for nearly 750 million tons of carbon dioxide equivalent (CO_2-eq.)in 2006, and represented over 12% of total CH_4 emissions [1,2].

Russia is the world's top emitter of CH_4 from the waste sector, followed by USA and China, representing 37.4 million tons of CO_2-eq. or 5% of total global CH_4 emissions in 2006 [3]. The generation of MSW in Russia tripled during the period 1980 to 2007, and has continued to rise due to high economical growth. In 2007, the annual production of MSW per capita in Russia was 440 kg, which is approximately half that in Western countries [4]. Currently, landfills are the primary means for disposal of MSW in Russia (Table 1).

Table 1. Composition and treatment methods of MSW in Russia.

Parameters	National average [a]	Federal district		
		Central	**Southern**	**North-Western**
Administrative center (city)	National average [a]	Moscow [a]	Rostov [b]	St. Petersburg [c]
Year	1996	1996	2001	2002
MSW composition (%)				
Paper	20.0–36.0	37.7	25.3	15.6
Glass	5.0–7.0	3.7	5.8	13.7
Metals	2.0–3.0	3.8	2.2	4.6
Plastics	3.0–5.0	5.2	11.6	11.3
Textile	3.0–6.0	5.4	2.3	3.8
Rubber and leather	1.5–2.5	0.5	1.0	1.0
Wood	1.0–4.0	1.9	0.4	0.8
Organic	20.0–38.0	30.6	45.9	34.9
Other	10.0–35.5	11.2	5.5	14.3
Waste generation				
Total(Mt/year)	37.5	2.5–3.0	0.35	1.06
Per capita (kg/year)	252	301	339	232
Treatment methods (%)				
Recycling	1.3	na	na	na
Incineration	2.2	na	na	na
Landfilling	96.5	>95.0	>90.0	>70.0

Sources: (a) [11]; (b) [12]; (c) [8].

It is worth noting that due both to the lack of accurate statistics, and also to the existence of thousands of unofficial landfill areas, the exact number of landfills in Russia is unknown [5]. A rough estimate shows that the area occupied by landfills in Russia is equivalent to eight cities of the size of Moscow, or more than 0.8 million hectares; although it does not cover too much space on a geographical scale [5-7]. Current waste disposal in Russia is causes many environmental problems in Russia and also affects neighboring countries. As an example, the huge amount of solid waste generated in the North-Western part of Russia, in St. Petersburg and Leningrad Oblast (region), has been identified as the most extensive source of pollution around the Baltic Sea [6].

Due to international collaboration and the development of federal and regional MSW management programs, there is now a visible trend towards improvement of current waste management practices in Russia [6,7]. Development of such projects has increased since Russia's ratification of the Kyoto Protocol in 2005. The shift from waste landfill disposal to alternative treatment methods within Russian waste management is expected to have positive impacts on global warming, not only directly by decreasing GHG emissions, but also indirectly by saving energy and materials from non-renewable resources. However, due to the lack of studies on municipal solid waste management system (MSWMS) in Russia, such aspects have not yet been considered. A few evaluating studies addressing waste management in Russia have been presented recently [5,8-10]. However, all of these studies considered only evaluation of GHG emissions resulting from waste landfilling as an independent operation, and have not considered assessment of other waste treatment options. These options are very closely interlinked and can influence the central components of the MSWMS, such as waste generation, separation, collection, and transportation.

This study is an effort to design an optimal waste management/utilization system and to assess the current waste management practices as one system. This study reports the main outcome of the evaluation analysis conducted for St. Petersburg city. As an analysis tool a linear programming (LP) model has been formulated to design and to evaluate MSWMS considering various waste treatment options. The comparison between the different scenarios has been performed taking into account energy, and the economic and environmental aspects, representing the sustainability of the proposed MSW utilization system.

2. Sustainable Waste Management and Waste Management Models

According to Tchobanoglous and Kreith [13], MSWMS is a complex process because it involves many technologies, associated with controlling generation, handling and storage, transportation, processing and final disposal of MSW under legal and economically acceptable social guidelines that protect the public health, and the environment. The main function of any MSWMS is the treatment of waste generated; where in addition, energy and recyclable materials can be recovered as by-products. Currently, MSW generated by households and economic activities is seldom used as a renewable energy resource. However, utilizing MSW in waste-to-energy (WTE) processes helps to mitigate GHG emissions generated from waste treatment by reducing CH_4 emissions. It also reduces the impact of GHGs as they replace fossil fuels in energy production activities.

Waste generation and disposal is generally considered as a major indicator of an unsustainable society. Based on waste hierarchy, the concept of sustainable waste management handles MSW in an

environmentally effective, economically reasonable and socially acceptable way [14]. The waste hierarchy represents the order of preference for main options of municipal solid waste management (MSWM) and has become a key waste management concept in many European countries [15]. Based on environmental merits the waste hierarchy indicates that some strategies/technologies for waste handling are more appropriate than others, and could have very different impacts on climate change, not only directly by a decrease in (GHG) emissions, but also indirectly by saving energy and materials from non-renewable resources [16,17].

The complexity of a MSWMS can be described by the number of relationships between the components in the system. Due to the complexity of MSWMS, computer models should be built as supporting tools to explain, control or predict the behavior of these systems, as well as to plan and assess waste management [18].Over the past decades, various evaluation techniques have been used to analyze MSWMS. These techniques include numerical solving methods, life cycle assessment (LCA), life cycle inventory (LCI), material flow analysis (MFA), input-output (IO) tables, and several optimization approaches, such as linear programming (LP), mixed integer programming (MIP), and dynamic programming (DP) [19-23].The first MSW models, from the period between the 1960s to the 1970s, were optimization models and mainly dealt with specific aspects of waste management, that included the routing of waste vehicle collection and the location of waste transfer stations [24]. Such models were limited to analyzing only one time period, one processing option, and a single waste generation source; making them unsuitable for long term planning [22,25]. Later, several computer models were developed for strategic planning to calculate recovery rates, costs and environmental impacts of MSWMS. In addition, there are studies involving technical, economic and environmental analysis in order to evaluate the potential energy production from MSW [26-28]. In the past ten years, the assessment of integration of WTE applications into existing energy systems has also been included in several studies [21,29].

MSW model applications highlight how waste can be used as an alternative way to landfilling and for reducing GHG emissions. The double role of MSW as a fuel and as a material that can be recycled, leads to a broader range of technologies for their treatment. This has given rise to a lot of different structures and solutions for MSW treatment systems.

In order to design the optimal MSWMS, several characteristics of the target area are required along with the aspects relating to MSW and its management, such as the annual amount of generated waste, waste composition and density, and an existence of treatment technologies. The following aspects may also be included: urbanization rate, waste composition, climatic condition, *etc.* [30]. It needs to be mentioned that the presence of a market for by-products, such as recycled materials, compost, and/or energy carriers produced from waste is another necessary aspect of the designed MSWMS. To be sustainable waste management needs to be appropriate to the local conditions of the target area with respect to economic, environmental and social perspectives. Social issues considered within waste management may include a variety of factors, such as household size, occupation, income, consumption patterns, willingness to separate at source, willingness and ability to pay and public acceptance of waste management plans, *etc.* [31,32]. However, the literature reviewed showed that the third aspect of sustainability has received less attention than the economic and environmental issues. Given that waste represents an important and easily accessible source of sustainable energy, assessment of energy generated from waste could be considered as an additional aspect of sustainable

waste management. This study considered the sustainability of MSWMS through energy, economic and environment components, namely the 3E's [33,34]. Such an approach can bring an important contribution to the improvement of MSWMS resulting in balances of environmental, economic and energy aspects.

3. Methodology

3.1. The Proposed MSW Management System

This study presents a MSW utilization system considering a set of representative waste treatment technologies widely applied in many countries. The performance of the proposed waste management system is evaluated taking into account the 3E's aspects. These parameters were chosen as a set of criteria characterizing the sustainable MSWMS. A general representation of the proposed system is shown in Figure 1. The system considers thermal and non-thermal waste treatment technologies and several demand sectors for by-products generated due to waste processing.

Figure 1. Proposed municipal solid waste management system (MSWMS) considering energy recovery.
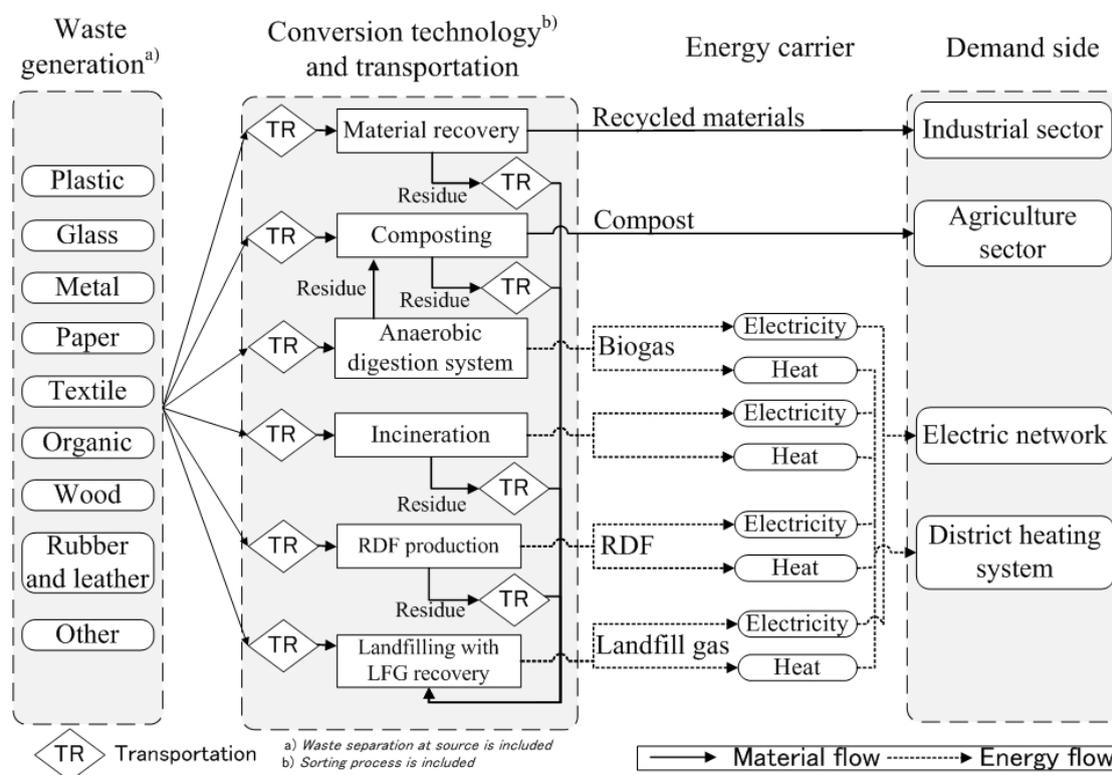

3.2. Description of the Optimization Model

This section describes the mathematical formulation of the LP optimization model used in the study. In order to determine the lowest cost structure of MSWMS, the model formulated in this study used a common LP technique often applied to solve waste management problems. As a specific point, incorporation of economic, environmental and energy (3E's) aspects, as well as the introduction of several constraints which emphasize the utilization of waste for energy and recycling purposes are

used to evaluate the sustainability of the designed system. Objective functions and model constraints are derived taking into consideration economic (total cost, revenue, unit treatment cost, *etc.*), environmental (CO_2-eq. emissions), and energy parameters (energy produced from waste).

The model formulated in this paper has been developed and implemented in GAMS (General Algebraic Modeling System), a tool, developed for solving mathematical programming and optimization problems [35]. The LP formulation of the optimization model, represented in Figure 2 is described below.

Figure 2. Schematic representation of the optimization model (*q*:quantity of waste material, *bp*:quantity of by-product).
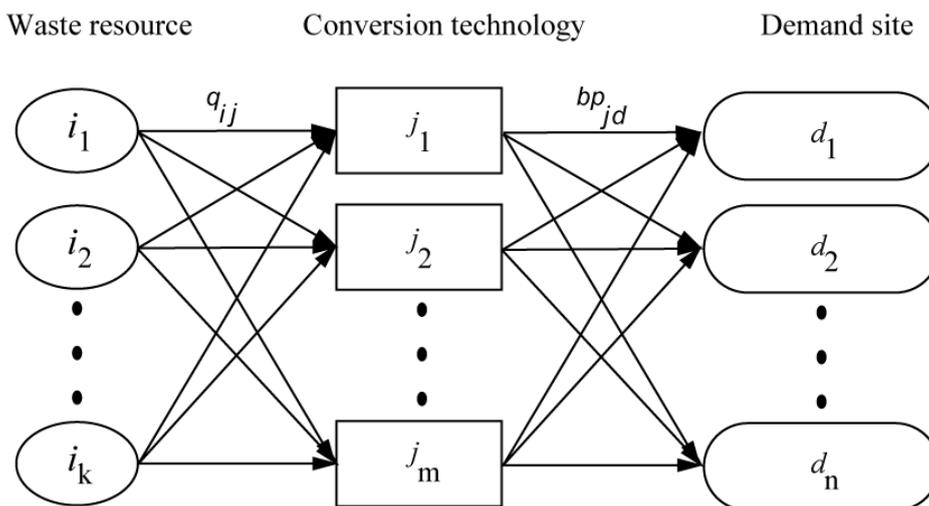
3.2.1. Objective Function

The objective function of the model includes minimization of the net cost of the proposed MSW utilization system defined as the difference between total cost and revenue, as described in Equations (1) and (2). The total cost of the MSW utilization system is calculated from the summation of the costs for collection / transportation, and treatment / landfill disposal. Revenue is derived from the selling of by-products, such as recyclable materials, compost, and energy generated by WTE facilities.

$$Min \sum_j nc_j = Min \sum_j (tc_j - b_{kj} \cdot p_k) \tag{1}$$

$$tc_j = \sum_i q_{ij} \cdot (C_{cap_j} \cdot CRF_j \cdot LF / T_{ot} + C_{om_j} + C_{tr_j} \cdot (d_j + fr_j \cdot dr_j)) \tag{2}$$

3.2.2. Features Evaluated by the Model

The developed model evaluates several aspects of the proposed MSW utilization system. These aspects, such as net cost, emissions and energy generated by the system represent the main sustainability features of the proposed MSWMS (Equations (3)–(5)).

(1) System net cost

$$nc_j = tc_j - b_{kj} \cdot p_k \tag{3}$$

(2) Environmental impact of the system

In order to assess emissions (CO_2, CH_4, and N_2O) from waste incineration, as well as emissions from other waste treatment technologies, IPCC methodology has been used in the present research [36]. According to this methodology, if incineration of waste is used for energy purposes, both fossil and biogenetic emissions should be estimated.

$$CO_2 = (\sum_j \sum_i q_{ij} \cdot emf_j + \sum_j \sum_i q_{ij} \cdot (d_j + fr_j \cdot dr_j) \cdot cap^{-1}_{tr} \cdot em_{tr}) \tag{4}$$

(3) Energy generated by the system

$$En = \sum_i \sum_j q_{ij}(LHV_i + LHV_{RDF} + \cdot LFG_{gr} \cdot eff_{coll} \cdot LVH_{LFG} + gas_{gr} \cdot eff_{coll} \cdot LVH_{gas}) \cdot \eta_{e,h} \tag{5}$$

3.2.3. Constraints

The model is subject to the following constraints:
(1) Mass balance constraints
All wastes generated in the study area should be transported to treatment plants or disposal site.

$$\sum_i q_i = \sum_j \sum_i q_{ij} \tag{6}$$

(2) Maximum capacity constraints
  These constraints consider that planned capacity at each facility should be less than or equal to the maximum allowable capacity of the facility.

$$\sum_i q_{ij} \leq T_{cap_j} \tag{7}$$

(3) Waste availability constraint
  The waste flow used in the model is subject to the components of each waste material. Because of the different characteristics of waste materials, each type of waste should be processed in the suitable treatment facilities as shown in Table 2.

$$q_{ij} \leq a_{ij} \cdot \sum_i q_i \tag{8}$$

(4) Waste utilization constraints
  These constraints represent a relation between total amount of waste generated in the target area and amount of waste materials allocated for recycling, composting, and energy production purposes.

$$\sum_e \sum_j \sum_i q_{ije} = rf_{WTE} \cdot \sum_i q_i \tag{9}$$

$$\sum_{m,c} \sum_j \sum_i q_{ijm,c} = fr_{WTR} \cdot \sum_j q_i \tag{10}$$

(5) Landfill disposal constraint
  This constraint defines the amount of waste allocated directly to landfill and untreated residues coming from other treatment facilities, which are to be transported to a final disposal site.

$$\sum_i q_{i,landfill} + \sum_j \sum_i q_{ij} \cdot fr_j = fr_{LFD} \cdot \sum_i q_i \tag{11}$$

(6) Non-negativity constraints

This constraint assures that only positive amounts of waste materials are considered in the solution.

$$q_{ij} \geq 0 \qquad (12)$$

Table 2. Sustainability of treatment technologies according to waste composition.

Treatment facility	Waste composition
Landfill	all types of waste
Incineration	all types of waste
Anaerobic digestion	paper, organic waste
Composting	organic waste, paper
RDF production	paper, plastic, wood, rubber and leather
Material recycling	paper, glass, metal, plastic, textile, wood, rubber and leather

3.3. Scenario Settings

In order to evaluate the impacts of different waste management options on the MSW utilization system, several scenarios were constructed in this study: A baseline or business as usual (BAU) scenario and four alternative scenarios are explained below. All scenarios are based on the same input data given for the generated amount of waste in the target area.

3.3.1. BAU Scenario (BAU)

The BAU scenario represents the existing MSWMS in the target area, and is the baseline upon which the results from other scenarios are compared.

3.3.2. Low cost Scenario (Low cost)

To achieve the optimal mix of treatment technologies with the minimal net cost of the proposed MSW utilization system, this scenario has been designed without considering regulation constraints, such as the desired amount of waste for recycling and/or for energy generation.

3.3.3. Max Energy Recovery Scenario (WTE)

In this scenario, the amount of waste allocated to energy production is maximized. In order to maximize the preference of energy produced from waste, the constraint on promoting the use of MSW for energy production is included in the model formulation.

3.3.4. Recycling Scenario (WTR)

The MSW utilization system presented in this scenario considers the maximum recycling capability of the proposed system. The constraint on the use of MSW for recycling purposes looking forward to increasing output of material recycled is considered in the model.

3.3.5. WTE&WTR

In this scenario high priority has been given to the energy generated from waste and the recycling of waste materials. Regulation constraints used in the model formulation have been defined as a combination of the average maximal value for the amount of waste used for energy production (50%), and the average material recycling rates (30%).

3.4. Study Area and Input Data

3.4.1. Study Area

A case study was conducted in the city of St. Petersburg, the third largest city in Europe after Moscow and London, and the second largest city in Russia. Also it is known as a major industrial center with a population of approximately 4.6 million. St. Petersburg is located on the Neva River at the head of the Gulf of Finland on the Baltic Sea and it is often recognized as the most western city in Russia (Figure 3).

Figure 3. Map of the target area: St. Petersburg city, Russia.
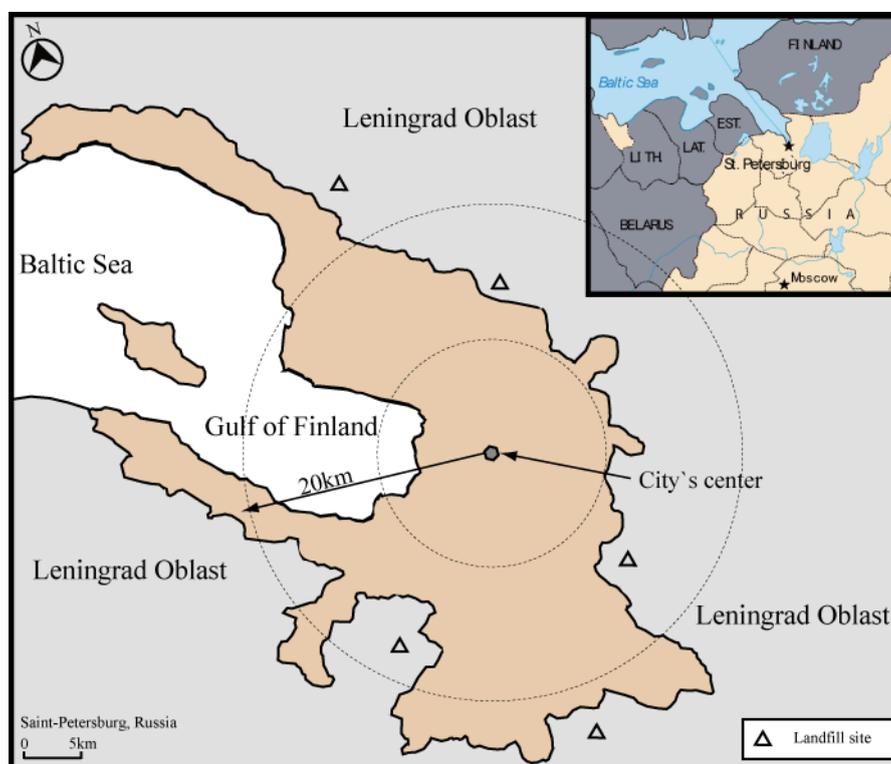
In recent years the population of St. Petersburg has decreased, however, due to economic growth the amount of MSW increased by 20% from 1994 to 2008 [8,37]. Annually, over 1 million tons of MSW is generated in St. Petersburg, from which over 70% is directly disposed in five disposal landfill sites located around the city [10]. In 2008 the annually collected amount of MSW was about 1.06 million tons, of which 25% was generated by commercial, and 75% by residential sectors (Table 3). Only a small amount went to the two waste treatment plants near the city. Insufficient waste treatment has

been recognized as a problem by city authorities and several Russian environmental agencies and NGO's. The major challenges within waste management in St. Petersburg are long transportation distances and improper treatment and storage of waste. Furthermore, the lack of a suitable waste utilization system in St. Petersburg causes many problems, such as a huge loss of useful materials, and emissions of many dangerous pollutants which have a significant influence on the environment inside and outside the city. St. Petersburg is responsible for 20% of the pollution in the Baltic Sea, where the MSW generated in the city is one of the main sources of this pollution [6].

Table 3. St. Petersburg data (2008).

Component	Data	
Population	4.6×10^6	
Total area	1.35×10^3	km^2
Average temperature	5.3	°C
Electricity demand	19,919	GWh
Heat demand	24,893	GWh
Share in heat demand		
Residential sector	58.96%	
Industrial sector	4.9%	
Transportation sector	0.8%	
Commercial sector	23.72%	
Other	11.62%	
MSW system		
Waste generation	1,065,775	t/year

Sources: [37-41].

In order to solve the problems of ineffective waste management in St. Petersburg, the administration of the city has developed several environmental measures, such as increasing the capacity of the present composting and recycling plants and building several new facilities, such as modern landfills and WTE facilities to process all waste generated in the city. Increasing waste separation at source is also one of such measures [42]. Given that St. Petersburg has a wide DHS network and an electrical grid; energy produced from MSW could be used as an energy source in the existing energy system located in the city.

3.4.2. Input Data

(1) Waste data

Generally, any MSW is composed of three groups of materials, such as organic waste (kitchen waste, garden waste, *etc.*), non-recyclable inorganic waste (dust, cinder, ash, *etc.*), and recyclable waste (paper, plastics, glass, metal, *etc.*). Typical composition of MSW in St. Petersburg and other Russian cities is shown in Table 1. It should be noted that organic waste is the main component of MSW in St. Petersburg representing more than 30% of the total waste. This study considers the nine largest fractions, totaling 98%, of the MSW currently generated in St. Petersburg, which are paper, glass, metal, plastic, textile, wood, organic waste, rubber, leather, and others. Current waste statistics data in Russia is based on volume measurements. For this reason the total annual amount of waste

generated in the target area has been estimated according to the average density of the MSW 232 kg/m^3. Since the data of the composition of the waste material and the heating values for each type of MSW generated in the target area was not available, it was estimated using the average data from several existing literature sources (Table 4).

Table 4. Waste related data in St. Petersburg.

Waste fraction	Composition (%)	LHV (MJ/kg) [a]	Carbon content (%) [b]	Fossil carbon content (%) [b]	LFG generation rate (Nm^3/t) [c]
Paper (mixed)	15.6	16.65	0.46	0.01	250
Plastics (mixed)	11.3	32.38	0.75	1.00	0
Glass	13.7	0.14	0.00	0.00	0
Metals	4.6	0.69	0.00	0.00	0
Organic (mixed)	34.9	4.63	0.38	0.00	250
Textile	3.8	17.35	0.50	0.20	250
Rubber and leather	1.0	20.24	0.67	0.20	0
Wood	0.8	18.50	0.50	0.00	35
Other	14.3	1.00	0.03	1.00	35
Total /Average	100.0	12.40	0.37	0.27	92

Sources: (a) [13]; (b) [36]; (c) [25].

(2) Treatment methods

The waste treatment technologies considered include landfilling of all types of waste with LFG extraction, incineration of all waste fractions with energy recovery, recycling of all types of waste except organic, anaerobic digestion and large scale composting of organic and paper waste (Table 5). The anaerobic digestion is assumed to be combined with composting facilities to increase the quality of composting product by including the digestate [43]. Each technology is characterized by several specific parameters, such as costs (capital investments, operation and maintenance), emissions coefficients, and types of generated by-products. The energy produced from incineration, and the biogas produced from landfilling and anaerobic digestion, is assumed to be used either for heating and/or for electricity generation. Electricity or heat produced from waste treatment processes is assumed to be supplied to the existing electrical grid or to the district heating system (DHS). DHS is widely expanding in Russia and is currently used to heat most buildings in urban areas and also partially in rural areas. St. Petersburg has the oldest and largest DHS network in the world which covers about 6,000 km [44,45].

(3) Economic aspects

By using a combination of data collected for St. Petersburg and data for waste treatment technologies adapted from several sources, transportation costs and treatment costs for each treatment facility have been calculated. The calculated costs of treatment facilities include the country location cost factor that represents the relative cost difference between two geographic locations. No personnel costs were considered in the analysis due to lack of available data. The revenue of the system is based on the sale of by-products, such as sorted materials, compost and generated energy. The selling prices of the by-products are the same as current values in the recycling and energy markets (Table 6). Transportation cost and selling prices of by-products were obtained for year 2008.

Table 5. Input data of technologies.

Treatment technology	Capital cost	O&M costs	Operation time	Residue rate
	USD/t	USD/t	Days/year	%
Incineration	800	0.6	292	20
Landfilling	200	0.1	360	100
Composting	250	0.2	292	0.5
Material recovery	200	0.3	292	10
RDF	200	0.3	292	15
Anaerobic digestion	1500	0.5	292	0

CRF = [i (1 + i) n]/[(1 + i) n − 1]; Operation life = 25 years, Discount rate = 11%; Thermal efficiency = 70%; Electrical efficiency = 20%; Heat losses = 15%; Electricity distribution losses = 10%; HVRDF = 12 MJ/kg; HVbiogas = 21 MJ/m3; HVLFG = 17.7 MJ/m3; Biogas collection efficiency =100%; LFG collection efficiency = 45%; Cost location factor = 1.47 (2007 year); Sources: [13,25,41,46].

Table 6. By-product's selling price.

By-product	Price	Reference
Heat, USD/MJ	0.0058	(a)
Electricity, USD/kWh	0.023	(a)
Compost, USD/t	53.57	(b)
Paper, USD/t	38.16	(c)
Plastic, USD/t	204.19	(c)
Glass, USD/t	45.08	(d)
Textile, USD/t	38.16	(e)
Ferrous materials, USD/t	229.01	(f)
* 1 USD = 25 RUB (2008)		

Sources: (a) [40]; (b) [47]; (c) [48]; (d) [49]; (e) [50]; (f) [51]

(4) Environmental aspects

This study focuses on emissions directly related to the waste treatment, transportation and energy production processes within MSWMS in the target area. The Global Warming Potential (GWP) concept that assesses the possible warming effects in relation to CO_2 equivalent on the atmosphere from the emission of each gas generated has been applied in this analysis. Based on IPCC methodology [36] and Tchobanoglous and Kreigh [13], the main GHG pollutants such as CO_2, CH_4, and N_2O have been evaluated.

3.4.3. System Boundaries and Major Assumptions

In order to obtain the optimal solution, the following assumptions were made in the model.

- The geographical boundary of St. Petersburg set the limits for the included type of waste streams, but there are no limits to location of the processing facilities.
- Current analysis is limited to the treatment of waste generated during a one year period. Constant residue rates have been set for all types of treatment technologies used in the present analysis.

- The waste source separation rate of 100% has been set for all types of waste materials. In addition, the average value for the recovery factors used for material recovery facilities is assumed to be 90% [13]. It needs to be noted, that the value set for recovery factor represents the maximum available rate which can be used in this technology. However, decreasing this rate may cause an increase of energy produced from MSW or/and increase in final disposal rate.
- The model assumes the average round trip transportation distance of 40 km and average cost of transportation of 2.1 USD/t/km associated with all waste treatment facilities. Waste materials accumulated in the collecting places are moved to the treatment and disposal sites using 11 tons trucks.
- Another important assumption of this model is the omission of the scale effect for the waste treatment facilities.

3.5. Sensitivity Analysis

Currently, the long distance of MSW transportation is pointed out among other things as one of the major problem within waste management in Russia [52,53]. In order to study the performance of the proposed MSW utilization system, the changes in the distance for waste transportation have been conducted as a sensitivity analysis.

4. Results and Discussion

4.1. Optimal Solution for Each Scenario

This section presents the results obtained from the calculation using a LP model, as well as an assessment of the 3E's aspects of the system in each scenario. For each modeling scenario the optimal solution representing designed MSWMS is calculated. The calculated results for the value of the objective function for the five different scenarios and evaluated aspects of the system are presented in Table 7. Figure 4 shows the changes in configuration of the proposed MSWMS. Results can be interpreted as follows.

Table 7. Main outcome from the analysis.

Component	Unit	Scenario				
		BAU	Low cost	WTE	WTR	WTE+WTR
Total system cost	M USD/year	111.31	129.76	165.78	131.91	127.92
Total revenue	M USD/year	2.12	51.96	28.17	53.29	43.49
Net cost	M USD/year	109.19	77.80	137.61	78.62	84.43
Unit treatment cost	USD/t	104.45	121.75	155.56	123.77	120.02
System emissions	M tons of CO_2-eq./year	1.32	0.401	1.16	0.155	0.83
Energy production	GWh/year	0	117.41	1188.25	25.67	266.06
fr_{WTE}	%	0	18	100	0.7	50
fr_{WTR}	%	11	68	0	85	30
fr_{LFD}	%	89	34	60	20	72

Figure 4. Changes in system configuration (all scenarios).
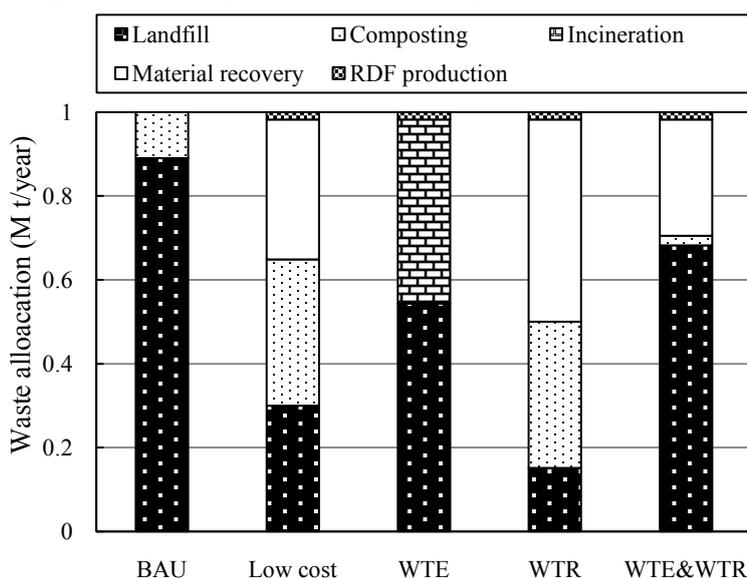
In the BAU scenario, it is assumed that there is no introduction of alternative waste treatment technologies, except existing low capacity treatment plants and landfills without LFG collection and recovery systems. Under this scenario, there is no energy production from waste and GHG emissions achieve the maximum value compared to other scenarios considered. Over 70% of waste materials generated in the target area are directly allocated to landfill site and the rest is processed in the composting and material recovery facilities (Figure 5). However, more than half of the composted material finally goes to landfill, due to low quality of the produced compost [8]. The low quality of the produced compost results because of the low efficiency of the separation and sorting process and the existence of glass, plastics and heavy metal in the final product. The final disposal rate in this scenario represents almost 90% of the total MSW generated.

Figure 5. Conventional MSWMS in St. Petersburg.
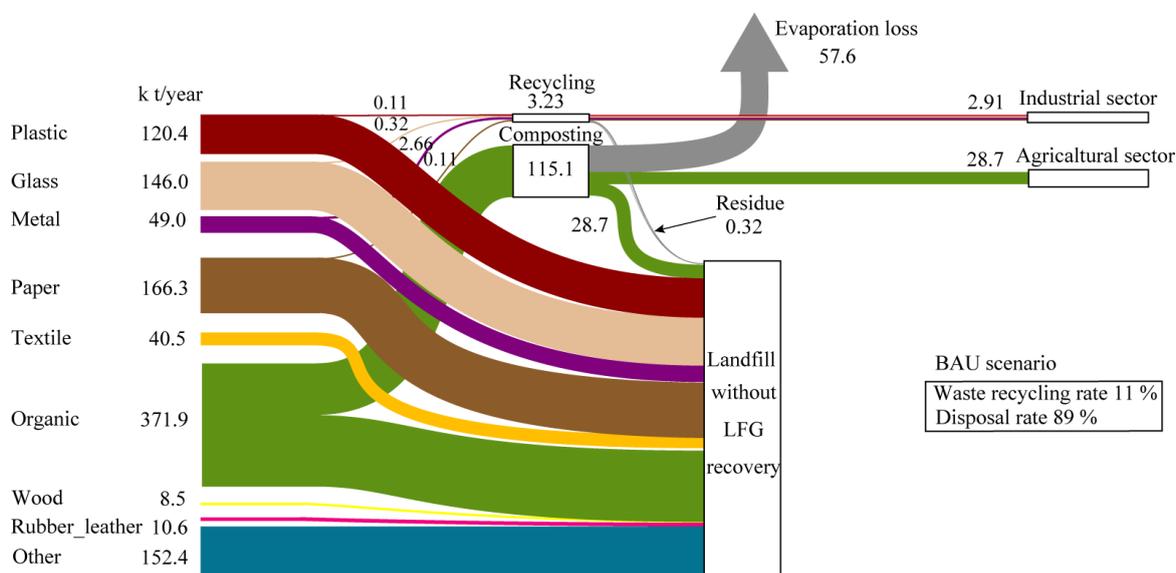
In order to achieve the optimal solution of the MSWMS under Low cost scenario, the majority of the waste flow (98%) is allocated between material recovery, composting and landfilling composed with LFG recovery systems. These technologies represent a central part of the designed waste management system.

The optimal system representing the best technology mix for the WTE scenario is mainly based on incineration and waste landfilling with LFG recovery. This scenario shows the complete utilization of waste for energy purposes without material recovery, except metal fractions collected from the ash.

As an alternative to waste landfilling, maximal recycling capability was introduced in the MSWMS designed under the WTR scenario. Waste flow allocated in material recovery and composting facilities represents more than 85% of total waste generated in the target area.

The design of MSWMS, with high priority given to energy produced from waste and material recycling is considered in the WTE&WTR scenario. Complete recovery of plastic, glass and metal waste, and low capacity composting facilities are introduced in this scenario. In contrast to the other designed scenarios, landfill facilities constructed with LFG recovery, represent the main WTE option.

In addition, the introduction of RDF production facilities in all designed scenarios was found to be the most economically feasible choice for treatment of waste materials, such as wood, rubber and leather.

4.2. Performance of the Designed System

In order to evaluate the sustainability of the designed MSWMS, the 3E's aspects, represented by net cost, energy and emissions generated by the system were evaluated. The BAU scenario representing the current MSWMS was used as a baseline for comparison. This scenario presents the minimal system cost (111.31 M USD/year) and a low level of revenue (2.12 M USD/year) generated from the system due to low recycling ability. As a result, the net cost of the system is high compared to the other designed scenarios. Unit treatment cost is equal to 104.45 USD/t. This scenario had the highest values of GHG emissions due to the large quota of waste landfilling without LFG recovery systems and represents 1.32 M tons of CO_2-eq. t/year or 1.23 tons of CO_2-eq./t. The cost of the waste management system mainly consists of transportation and treatment costs. Transportation cost is equal to 88.5 M USD/year or 80% of the total cost for waste management.

The optimal MSWMS which considers a mix of alternative waste treatment methods is represented by the Low cost scenario. This scenario with no limitation on the amount of waste for recycling and for energy generation represents the best solution or best scenario in comparison with other designed scenarios. The objective function of the best solution has a total value of 77.80 M USD/year or 72.9 USD/t. The introduction of alternative waste treatment technologies has an effect on the system cost and emissions Thus, the system cost and the unit treatment cost increase more than 15% compared to the BAU scenario and reaches values equal to 129.76 M USD/year or 121.75 USD/t. Moreover, CO_2 emissions decreased by 70% in this scenario, resulting from the improvement of recycling activities.

From an energy point of view, the best strategy is the WTE scenario, representing maximal amount of energy (1,188.25 GWh/year) produced from waste. Although the WTE scenario considers maximal utilization of waste for energy production; it does not show a significant reduction of system emissions (1.16 M tons of CO_2-eq./year or 1.08 tons of CO_2-eq./t). This scenario shows the highest system cost

(165.78 M USD/year) and unit treatment cost (155.56 USD/t) with little environmental benefits in comparison to the BAU scenario. The energy generated from MSW may substitute fossil fuels and reduce GHG emissions resulting from energy activities. Currently, natural gas (with share of 97%) represents the main fossil fuel resource used for energy generation in the target area. The energy produced under the WTE scenario represents 2.5% of the total annually consumed energy (44,812 GWh/year) in St. Petersburg. Moreover, replacing the energy generated from fossil fuels results in a 3% decrease in GHG emissions resulting from the energy sector.

A common treatment technology used by all designed scenarios is material recovery, representing the major source of income of the proposed system. The WTR scenario with a high level of materials recovery shows the highest amount of revenues from the sale of recycled materials equal to 53.29 M USD/year. In terms of CO_2 emissions, results obtained from this scenario showed that the introduction of a high recycling rate ultimately reduces GHG emissions up to 0.15 M tons CO_2-eq./year. This result was obtained by considering several assumptions related to the waste collection and separation, and represents an unrealistic scenario compared with the present situation in St. Petersburg. Currently, the selective collection of MSW is not well organized in the target area, however there are several programs coordinated by the municipality, and improvement of the source separation of waste is expected. In addition, changes in policy, the improvement of the recycling efficiency of treatment facilities, and the improvement of households with regard to recycling processes could achieve feasible goals. Due to the lack of suitable data associated with the types and composition of waste materials generated in St. Petersburg, compensative effects, such as substitution of raw materials, resulting from the recovery of waste materials has not been considered in the present analysis.

The targets set for the WTE&WTR scenario are close to the real targets which can be set in St. Petersburg in order to solve the current waste management problem. Figure 6 illustrates waste material flow and energy flow of the optimal MSWMS, designed for the WTE&WTR scenario while considering the introduction of regulation constraints for waste utilization. More than 60% of total waste generated in the target area is allocated to landfilling with a LFG recovery system. The rest of the waste materials are allocated between recycling, RDF and composting facilities. The results of this scenario show that due to low market price, recycling of waste paper is not an economically favorable option. In this scenario, the landfill site plays a significant negative role as a main contributor of GHG emissions generated by the designed MSWMS. Based on the assumption that only 45% of LFG produced is effectively recovered, the remaining 55% is released into the atmosphere. CO_2 emissions generated by landfill sites represent over 90% of total emissions (0.83 M tons of CO_2-eq./year) produced by the system. Compared to other designed scenarios, this scenario represents the minimal system costs (127.92 M USD/year) and unit treatment cost (120.02 USD/t).

Figure 6. The optimal MSW utilization system (WTE&WTR scenario). (**a**) Waste material flow; (**b**) Energy flow.

(**a**)

(**b**)
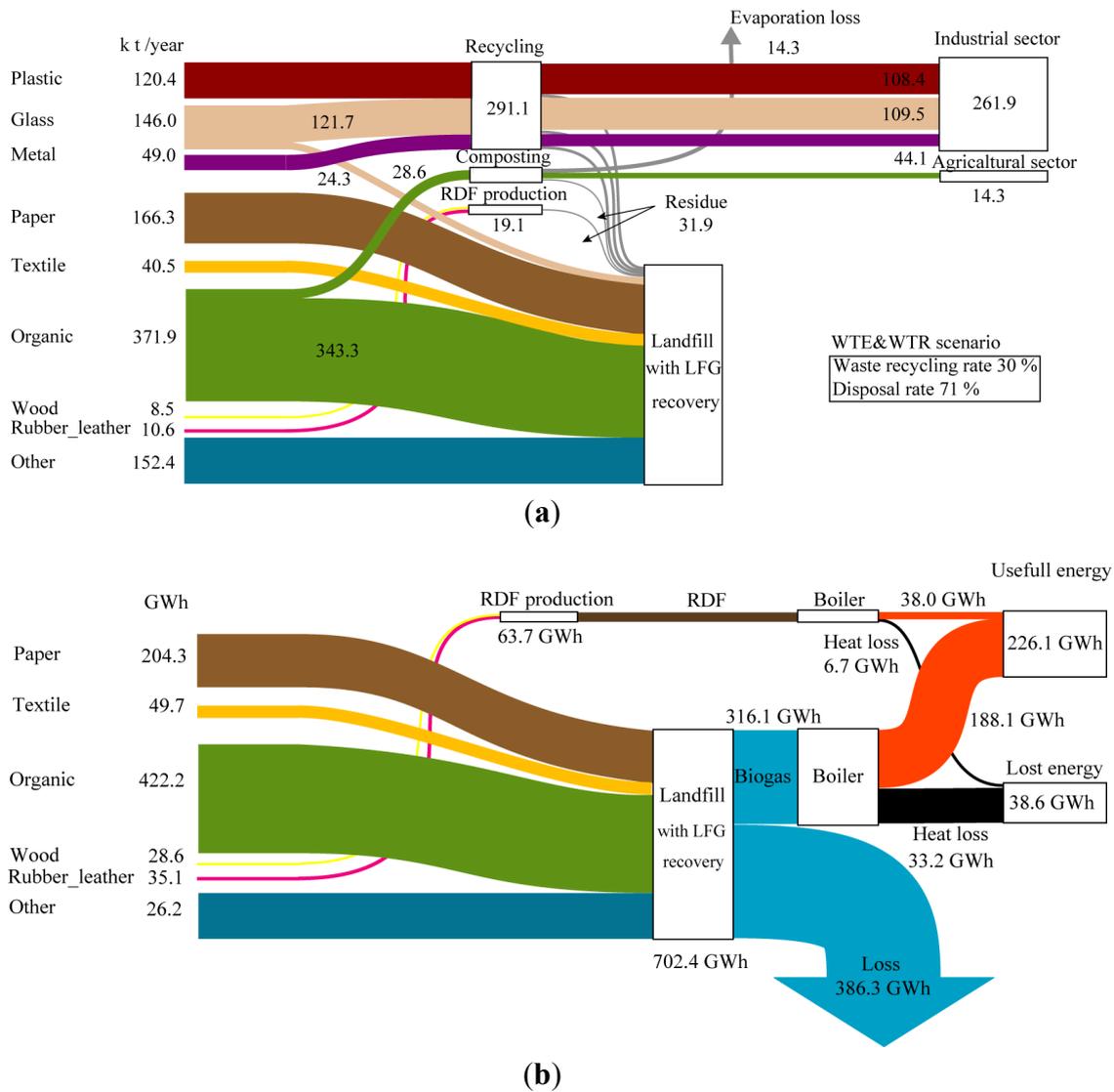
According to the calculation results, transportation costs consume the largest portions of the total cost of the proposed MSW utilization system. From the sensitivity analysis of the best scenario (Low cost), it can be seen that changes in waste transportation distance have a significant effect on the cost of the proposed MSW system (Figure 7). Moreover, it can be concluded from the results that the increase of the waste transportation distance will result in a decrease of the system revenue and growth of the final disposal rate due to reduction of recycling activity. For example, if the waste transportation distance increases by 10 km, the final disposal rate grows sharply by more than double. On the other hand, smaller distances for waste transportation, resulted in the growth of the waste recycling rate, and a decrease in waste to energy and final disposal rates (Figure 8).

Figure 7. Effect of changes in system costs for different transportation distance (Low cost scenario).
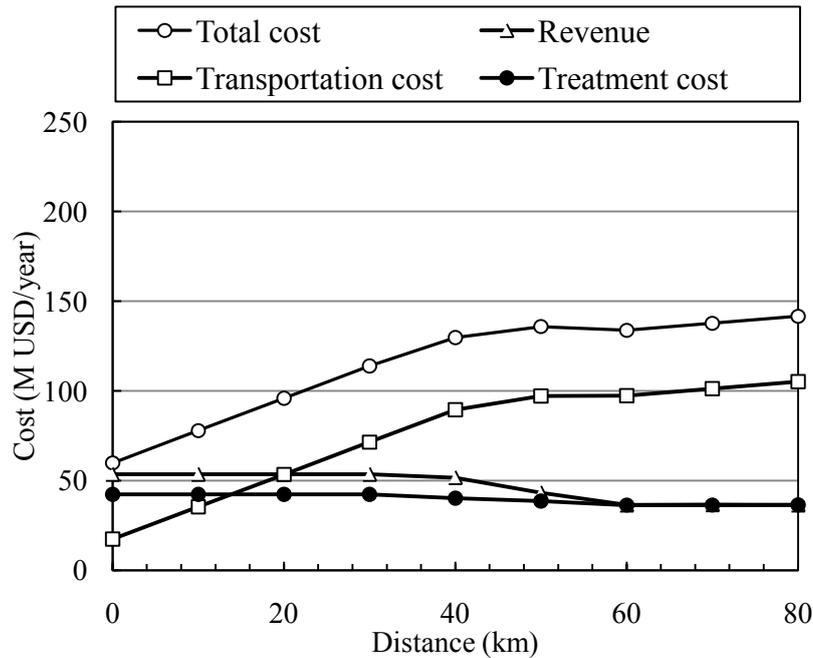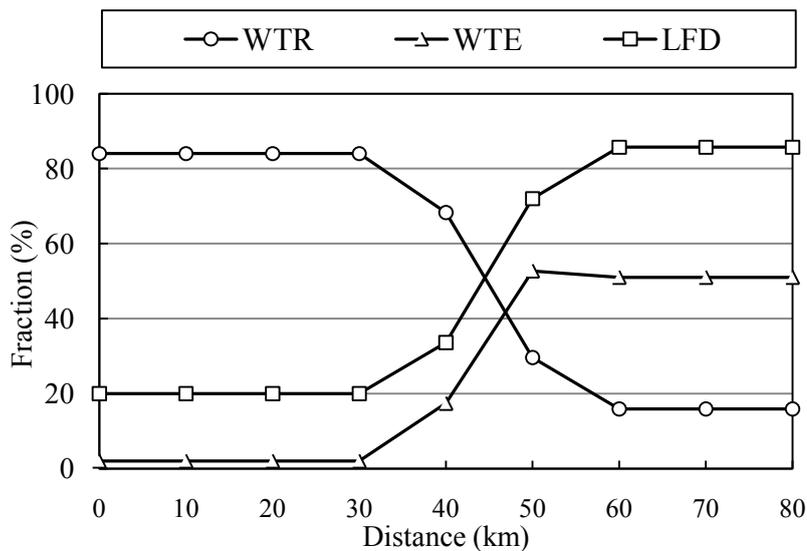

Figure 8. Changes in system performance for different transportation distance (Low cost scenario); fr_{WTR}: *fraction* of waste allocated for recycling; fr_{WTE}: fraction of waste allocated for energy production; fr_{LFD}: *fraction* of materials (waste and residues) allocated for landfill disposal.

Introduction of new waste treatment technologies would reduce the total system emissions. All developed scenarios give a significant reduction of GHG compared to the BAU scenario. The best way to achieve maximum GHG reductions (more than 50%) from the system is to apply the WTR scenario based on the assumption that the maximum amount of waste is recycled, with a high recycling rate at more than 80%. This effect is due to the reduced emissions of LFG from landfills. From an economic

point of view, the WTR and Low cost scenarios allow the highest revenue from the sale of the by-products generated from the waste treatment process. Finally, the optimal balance between the amount of waste allocated to energy production and recycling can be achieved in the WTE&WTR scenario. The achieved results demonstrate that the presence of an LFG recovery system, as a WTE treatment option, has a significant influence on the modeling results. As an alternative to landfill, anaerobic digestion systems and incineration were not included in the technology mix calculated in the model. One of the possible reasons is the high cost compared to other waste treatment technologies. In order to introduce such a technology, additional financial instruments or policies have to be implemented, such as landfill tax, or carbon tax. Due to the low price of electricity generated from fossil fuels, the results of the study show that the energy recovery from waste in the form of electricity is not involved in the optimal solution for the designed MSWMS.

5. Conclusions

In this research, the municipal solid waste management system in St. Petersburg has been modeled while considering the introduction of alternative waste treatment facilities. The model has been solved using the GAMS software.

- This study indicates that an increase of alternative MSW treatment options gives positive energy, and economical and environmental benefits compared with the present MSWMS.
- Recycling of the MSW was the main waste processing option in the model results. Introduction of recycling is an appropriate solution to manage the increasing amount of waste generated by society. Theoretically the consumers may be motivated to increase the source separation rate of MSW if forced to pay for each kg of waste. However, because of a lack of equipped collection places for separated waste materials this does not currently seem realistic in St. Petersburg or other Russian regions [54]. Another way to involve the population in the waste separation process is the introduction of customer benefits, such as introducing low collection and transportation fees for completely separated waste. Incentives, such as the introduction of financial support to stimulate the development of markets for recovered materials with more stable market prices, could also increase recycling rates.
- Heat generated from waste treatment processes was the most optimal energy carrier according to the results of the calculation as it was assumed in this study, the heat generated from waste is supplied to DHS because of the existing heat transfer network. However, in Russia however, typical district heating distribution for space heating is operational for only part of the year from October to April [55]. During the summer period, the heat generated from MSW could be used for water heating. This would then bring an additional benefit due to reduction of GHG emissions generated from the consumption of fossil fuels.
- The main limitation of this paper is the quality of input data. The actual optimal solution can be reached only with highly detailed data for the target area. The results of the presented model are based on some assumptions in the absence of the available data, such as waste composition, heating values, and waste transportation distance. This could change with more accurate data. In addition, consideration of compensative effects related to material recycling and energy production from waste may have a strong influence on the output results of the model.

For further research on MSW management in other regions of Russia, the model can be easily modified to meet local conditions; however the model accuracy is directly proportional to the set of detailed input data. Regional differences, such as climatic conditions, location, urbanization rate, waste compositions, transportation distance, and existence of markets for by-products, are an important feature of the designed system. In order to design an optimal MSW utilization system in other regions of Russia, regional differences must be considered as a major feature of the system.

Acknowledgments

References and Notes

1. Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2007: Mitigation Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A., Eds.; Cambridge University Press: Cambridge, UK, 2007.
2. United States Environmental Protection Agency (US EPA). *Global Anthropogenic Emissions of Non-CO_2 Greenhouse Gases 1990-2020*; US EPA: Washington, DC, USA, June 2006.
3. United States Environmental Protection Agency (US EPA). *Global Mitigation of Non-CO_2 Greenhouse Gases*; US EPA: Washington, DC, USA, 2006.
4. Organisation for Economic Co-operation and Development (OECD). *Factbook 2009: Economic, Environmental and Social Statistics*; OECD: Paris, France, 2009.
5. Kalyuzhnyi, S.; Epov, A.; Sormunen, K.; Kettunen, R.; Rintala, J.; Privalenko, V.; Nozhevnikova, A.; Pender, S.; Colleran, E. Evaluation of the current status of operating and closed landfills in Russia, Finland and Ireland with regard to water pollution and methane emission. *Water Sci. Technol.* **2003**, *48*, 37-44.
6. Schiessler, N.; Eldridge, J.; Roben, E. *LIFE-Third Countries 1992-2006: Supporting Europe's Neighbours in Building Capacity for Environmental Policy and Action*; European Commission Environment Directorate: Luxembourg, European Communities, 2007.
7. FINPRO. *World Bank Financed Waste Management Projects: Overview of the Waste Management Markets and Trends in Developing Countries and Prospects for Finnish Companies*; FINPRO: N.W. Washington, DC, USA, 2004.
8. Florinskaya, T.M.; Ventzulis, L.S.; Vechtomov, I. *Conception - Waste management in St. Petersburg*; Academy of Science of Russian Federation, St. Petersburg Scientific Centre: St. Petersburg, Russia, 2002; p. 189.
9. Kalyuzhnyi, S. Municipal Solid Waste Management in Russian Federation: Status and Perspectives. In *Proceedings of the European Workshop: Impact of Waste Management Legislation on Biogas Technology*, Tulln, Austria, 12–14 September 2002.

10. Lappalainen, S.; Kouvo, P. *Evaluation of Greenhouse Gas Emissions from Landfills in the St. Petersburg Area. Utilization of Methane in Energy Production, Metgas.*; Lappeenranta University of Technology: Lappeenranta, Finland, 2004.

11. Cherp, O.M.; Vinichenko, V.N. Problem of municipal solid waste. In *Ecoline (Ecoline Environment Assessment Center)*, Moscow, **1996**.

12. Privalenko, V.V. *Current Status of Landfills in Rostov-on-Don and Surrounding Areas.* Half year report for INCO Copernicus grant ICA2-CT-2001-10001: Bratislawa, Slovak Republic, 2001.

13. Tchobanoglous, G.; Kreith, F. *Handbook of Solid Waste Management*, 2nd ed.; McGraw-Hill: New York, NY, USA, 2002.

14. McDougall, F.R.; White, P.R.; Franke, M.; Hindle, P. *Integrated Solid Waste Management: A Life Cycle Inventory*, 2nd ed.; Blackwell Science: Oxford, UK, 2001.

15. Jamasb, T.; Nepal, R. Issues and options in waste management: A social cost-benefit analysis of waste-to-energy in the UK. *Resour. Conserv. Recycl.* **2010**, *54*, 1341-1352.

16. Mondini, C.; Sanchez-Monedero, M.A.; Cayuela, M.L.; Stentiford, E. Soils and waste management: A challenge to climate change. *Waste Manag.* **2008**, *28*, 671-672.

17. Schmidt, J.H.; Holm, P.; Merrild, A.; Christensen, P. Life cycle assessment of the waste hierarchy—A Danish case study on waste paper. *Waste Manag.* **2007**, *27*, 1519-1530.

18. Tanskanenn, J.H. Strategic planning of municipal solid waste management. *Resour. Conserv. Recycl.* **2000**, *30*, 111-133.

19. Nakata, T.; Rodionov, M.; Silva, D.; Jupesta, J. Shift to a low carbon society through energy systems design. *Sci. China Technol. Sci.* **2010**, *53*, 134-143.

20. Diaz, R.; Warith, M. Life-cycle assessment of municipal solid wastes: Development of the WASTED model. *Waste Manag.* **2006**, *26*, 886-901.

21. Luoranen, M.; Horttanainen, M. Co-generation based energy recovery from municipal solid waste integrated with the existing energy supply system. *Waste Manag.* **2008**, *28*, 30-38.

22. Chang, N.B.; Wang, S.F. Solid waste management system analysis by multiobjective mixed integer programming model. *J. Environ. Manag.* **1996**, *48*, 17-43.

23. Gielen, D.J. The MARKAL Systems Engineering Model for Waste Management. In *Proceedings of the International Workshop Systems Engineering Models for Waste Management*, Goteborg, Sweden, 25-26 February, **1998.**

24. Morrissey, A.J.; Browne, J. Waste management models and their application to sustainable waste management. *Waste Manag.* **2004**, *24*, 297-308.

25. Daskalopoulos, E.; Badr, O.; Probert, S.D. An integrated approach to municipal solid waste management. *Resour. Conserv. Recycl.* **1998**, *24*, 33-50.

26. Dornburg, V.; Faaij, A.P.C.; Meuleman, B. Optimising waste treatment systems: Part A: Methodology and technological data for optimising energy production and economic performance. *Resour. Conserv. Recycl.* **2006**, *49*, 68-88.

27. Dornburg, V.; Faaij, A.P.C. Optimising waste treatment systems: Part B: Analyses and scenarios for The Netherlands. *Resour. Conserv. Recycl.* **2006**, *48*, 227-248.

28. Ljunggren Soderman, M. Recovering energy from waste in Sweden—A systems engineering study. *Resour. Conserv. Recycl.* **2003**, *38*, 89-121.

29. Holmgren, K.; Henning, D. Comparison between material and energy recovery of municipal waste from an energy perspective: A study of two Swedish municipalities. *Resour. Conserv. Recycl.* **2004**, *43*, 51-73.

30. Dayal, G.; Yadav, A.; Singh, R.P.; Upadhyay, R. Impact of climatic conditions and socio-economic status on solid waste characteristics: A case study. *Sci. Total Environ.* **1993**, *136*, 143-153.

31. Nilsson-Djerf, J.; Mcdougall, E. Social factors in sustainable waste management. *Warmer Bull.* **2000**, *73*, 18-20.

32. Desmond, M. Municipal solid waste management in Ireland: assesing for sustainability. *Ir. Geogr.* **2006**, *39*, 22-33.

33. Dorf, R.C. Energy, Environment, Economy, and Society. In *Technology, Humans, and Society*; Academic Press: San Diego, CA, USA, **2001**; pp. 223-239.

34. Yoda, S. *Trilemma: Three Major Problems Threatening World Survival*. Central Research Institute of Electric Power Industry: Tokyo, Japan, **1995**.

35. Brooke, A.; Kendrick, D.; Meeraus, A.; Raman, R. *GAMS—A User's Guide*; GAMS Development Corporation: Washington, DC, USA, **1998**.

36. IPCC. *Guidelines for National Greenhouse Gas Inventories*; Intergovernmental Panel on Climate Change (IPCC): Geneva, Switzerland, **2006.**

37. FSS. *The Basic Social and Economic Indices of Cities in 2008 (in Russian)*; Federal State Statistics Service of Russian Federation: Moscow, Russia, 2008.

38. FSS. *Electricity consumption per region of Russian Federation*; Federal State Statistics Service of Russian Federation (FSS): Moscow, Russia. Available online: http://www.gks.ru/free_doc/new_site/business/prom/el_potr.htm (accessed on 25 August 2011).

39. FSS. *Estimation of Resident Population of Subjects of Russian Federation*; Federal State Statistics Service of Russian Federation: Moscow, Russia, 2010.

40. TGC-1. *Annual Report 2008*; Territorial Generating Company N1 (TGC-1): Saint Petersburg, Russian Federation, Russia, 2009.

41. TGC-1. *Kharakteristika Teplovih Moschnostei Regiona (in Russian)*; Territorial Generating Company N1 (TGC-1): Saint Petersburg, Russian Federation, Moscow, Russia; Available online: http://tgk1.ru/clients/sbyt/ (accessed on 12 December 2010).

42. The government of St. Petersburg. *Environmental Policy of St. Petersburg for the Years 2008-2012*; Committee for nature use environmental protection and ecological safety, Ecological portal of St. Petersburg: St. Petersburg, Russia, 2007.

43. Monnet, F. *An Introduction to Anaerobic Digestion of Organic Wastes*; Remade Scotland. The European Biogasmax project: Glasgow, UK, November 2003.

44. Gochenour, C. *District Energy Trends, Issues, and Opportunities: The Role of the World Bank*; World Bank Publications: Washington, DC, USA, 2001; Volume 493.

45. Kokki, S.; Friari, P.; Zarkzhevsky, V.; Horttanainen, M.; Linnanen, L. *Reduction of Greenhouse Gas Emissions in North-West Russia—Finnish Business Opportunities*; Lappeenranta University of Technology, Department of energy and environment technology: Lappeenranta, Finland, 2006.

46. CDOL. *Richardson Cost Factors—Location Cost Manual*; Cost Data On Line (CDOL): Pahrump, NV, USA, 2008.

47. LLC "Sofora" Garden company "Sofora". http://www.sofora.ru/pesok_sheben.html (accessed on 12 December 2010).

48. JSC "Rosstan" Manufactures' equipment company. http://www.rosstan.ru/catalog/oborud/press/pat/index.php (accessed on 12 December 2010).

49. JSC "Clean town" web-site. Available online: http://clentown.ru/ (accessed on 12 December 2010).

50. Industrial Group "Statico". http://www.statico.ru/about.htm (accessed on 12 December 2010).

51. ZAO "Otraslevie vedomosty" "Municipal solid waste". http://www.solidwaste.ru/projects/vtorprice/4.html (accessed on 12 December 2010).

52. Abramov, N.F. Waste Management and Recycling Market in Russia. In *Proceedings of the International Exhibition and Conference for Waste Management, Recycling, Renewable Energy and Environmental Technologies, WasteTech-2005*, Moscow, Russia, 31 May-3 June, 2005.

53. Fedorov, M.P.; Chusov, A.N. Municipal Solid Waste Management System in Saint Petersburg (Russia). In *Proceedings of 7th International Waste Management and Landfill Symposium*, Sardinia, Italy, 1-5 October, 2007.

54. Babanin, I.V. Experience of impementing the system of selective collection of MSW in Saint Petersburg. Greenpeace Russia. Available online: http://baltfriends.ru/node/101 (accessed on 1 September 2010).

55. GMBK, *The government of St. Petersburg.Gorodskaya mezhvedomstvennaya komissiya (GMBK). Pravila podgotovki i provedeniya otopitelinogo sezona v Sankt-Peterburge (in Russian)*. Power and Engineering maintenance committee: St. Petersburg, Russia, 2006.