

Article

Expansion of the Fuel and Energy Balance Structure in Russia through the Development of a Closed-Loop Recycling

Olga Novikova ¹, Iaroslav Vladimirov ^{1,*} and Tatiana Bugaeva ²

¹ Institute of Energy, Graduate School of Nuclear and Thermal Power Engineering, Peter the Great Saint-Petersburg Polytechnic University, 195251 Saint Petersburg, Russia; novikova-olga@spbstu.ru

² Institute of Industrial Management, Economics and Trade, Graduate school of Industrial Economics, Peter the Great Saint-Petersburg Polytechnic University, 195251 Saint Petersburg, Russia; bugaeva@spbstu.ru

* Correspondence: vladimirov@nil-teplo.ru

Abstract: The goal of the study is to propose the basis for the concept of expanding the fuel balance in Russia through the development of a closed-loop resource cycle. We propose to use the criterion of energy potential of waste to generate new data on the resource base of the fuel and energy complex at the regional level. In order to form a reliable source for replenishment of the resource potential of the fuel and energy complex through waste recovery, the basic principles of data collection are proposed and the methodology for determining the energy potential at the city level is demonstrated using municipal solid waste (MSW) in 11 Russian cities as an example. The results of the evaluation have shown that due to energy recycling, MSW can cover from 2.11% to 6.01% of the heat demand of the territory under consideration. In the study, we propose to supplement the maximum involvement of waste in the fuel and energy balance (FEB) in Russia with the criterion of optimization of the energy balance at all levels and to distinguish a separate column “energy potential of waste” in the balance structure. This approach fundamentally changes the structure of the balance and gives the grounds for revision of plans for production and transportation of traditional energy resources.

Keywords: energy potential; municipal solid waste; waste treatment; energy use of waste; energy sources



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1. Introduction

The process of production and consumption of products generates large volumes of waste, which is based on unused raw materials. However, in today's thinking, technology, and organization of production in the countries with high stock of hydrocarbons, these waste resources are treated in accordance with their economic effect, even including landfilling. The technological advancements of society are mainly based on the use of primary resources and therefore the applied technologies have an open-loop cycle [1,2].

The waste from production and consumption must again turn into raw materials, and these raw materials be assembled into a product again. This is the main idea of a closed-loop resource cycle (CLC). Recycling and neutralization of waste are not identical concepts according to legal practice [3]. Neutralization includes, for example, processes such as burial of MSW or pyrolysis (thermal decomposition without oxygen access). There is a problem of ensuring a comprehensive approach based on a single concept of returning all the types of waste into the resource cycle and of specification of innovative technological development according to the new concept, which facilitates waste division into suitable and unsuitable for energy use.

To understand the scale of the task, we should note that the global market of waste management, excluding the mining segment, currently exceeds \$1.1 trillion with an expected growth rate of 7–10% per year in the short term. In a regional context, 45% of the market is in Asia, 35% in the EU, and 15% in the North and South America [4]. In 2015,

84% of the market (\$950 billion) was in the industrial and construction waste segment, and 16% in the MSW segment. According to the latest estimates, about 3000 million tons of different types of waste are generated annually in Europe. This corresponds to 3.8 tons of waste per capita in Western Europe, 4.4 tons in Central and Eastern Europe, and 6.3 tons in Eastern Europe, the Caucasus, and Central Asia [4]. Each European country has its own recycling level. The largest amount of waste (30% to 50% and more) is recycled in Sweden, Denmark, Switzerland, Germany, Belgium, Norway, Austria, and the Netherlands. The UK, Iceland, Portugal, and Greece have the lowest (up to 15%) recycling levels [5]. Each year, countries are trying to increase the amount of recycled waste. Despite this, landfilling is still a common practice in many countries. In developed countries, waste is considered a strategic resource for the production of heat and electricity, metals, and other valuable materials [6,7]. In order to reduce the number of landfills, Sweden introduced a tax on landfilling in 2000, a ban on the disposal of explosive substances in 2002, and a ban on the disposal of organic waste in 2005 [8]. Later, Sweden introduced a tax on incineration of domestic waste. In Sweden, waste plays an important role in the country's heating system. In 2015, Sweden produced 17 TWh of energy through recycling: 14.7 TWh of heat and 2.3 TWh of electricity. Today, more than 2 million tons of waste are incinerated in Sweden. Even with such high numbers of local raw materials it is not enough; the country tries to cover the deficit through importation. In terms of technical level, the waste management system in Germany is one of the most advanced in the world. There, more than 90% of domestic waste is recycled, even though the European average is 37%. The overall recycling level of various materials in Germany is above 80%. In 2016, 68% of paper, 94% of glass, and 45% of steel were produced from recycled materials [9].

In 1997, Denmark became the first country in the world to legally prohibit landfilling of waste that can be incinerated to generate heat and electricity [10]. Since then, dozens of incineration plants have been built. Denmark ranks first in Europe in terms of "kilogram per capita per year" [11]. Over time, a system has emerged that has been recognized worldwide as the "Danish Waste Model". Its basic elements and features include:

- an integral and consistent system of legal regulation, public administration, planning, and public control;
- division of roles, responsibilities, and competencies between national, regional, and local authorities, waste generators, and waste management companies;
- a well-developed structure for all waste management activities.

In addition, Denmark has adopted the so-called "Energy Agreement" aimed at ensuring Denmark's full independence of fossil fuels by 2050, which is expected to result in a significant increase in funding allocated to bioenergy projects [12].

A special feature of the Asian trend of waste treatment development is the use of the obtained materials for the construction of infrastructure—Odaiba Island in Japan is a good example [6]. Speaking about foreign practice of developing the sphere of recycling, it should be said that in a number of countries, the leading role is given to the state. However, not only the center of the country is involved in recycling and provided with necessary equipment, but provinces or municipalities are also directly involved. Besides, private business also plays a significant role [13]. The benefits of government leadership are precisely that these countries have specialized programs supporting the waste treatment sector, as well as the actors involved.

For a long time, garbage containers in China consisted of two compartments: recyclable waste and other waste. In 2017, fines for wrong sorting of waste appeared in China, both for companies and common citizens. Innovations began in Shenzhen: since October 2017, citizens who refuse to sort domestic waste are charged a fine of CNY 50 (Yuan) (about USD 7), organizations are charged up to CNY 1000 (USD 145). In the USA, as in Germany, there is a whole system of penalties depending on the state. Proper sorting, however, is handled by specialized organizations, and Americans only need to dispose of food waste separately [9].

The share of recycling in the EU countries in 2004 and 2017 (% of total MSW generated) [5] increased from 36% to 55%.

One of the most important issues of waste management is waste classification. Most countries and regions have developed their own waste classification systems. Although different waste classification systems exist in the EU, Japan, USA, and Russia, there is one classification applicable worldwide, namely, the Basel Convention, including classifications for hazardous waste and nonhazardous waste [14]. Waste management practices can differ for developed and developing nations. A good waste classification system is the foundation and precondition for efficient waste management.

Russian scientific literature has dealt with the problem of waste. It mainly involved analysis of the situation in the field of municipal solid waste [15,16]. Economic issues related to the generation and accumulation of production and consumption waste, the comparison of the Russian sphere waste management with foreign countries, and the analysis of legislation and its reform are considered in [17,18] and other works. Analysis of publications [19–23] shows the inconsistency of data on the volumes of waste and the lack of a unified methodological approach to assessing the energy potential of waste, both in various structures dealing with waste disposal in the Russian Federation and between the state bodies collecting, systematizing, and analyzing statistical information. Moreover, according to the report of the Russian Federation Accounts Chamber, by 2024, 32 of 85 Russian regions will run out landfill capacity by 2024, and 17 of them by 2022, which makes the problem of waste recycling extremely acute [24].

In many countries with high population density, where there is insufficient space for landfills, opportunities to landfill unsorted municipal solid waste are limited. An alternative is thermal methods of utilization and, foremost, the use of MSW as a fuel with the production of electric and thermal energy. Russia lags far behind in the field of energy utilization of solid waste. The fuel and energy balance of Russia currently does not take into account the energy potential of waste of various origins.

The goal of our study is to propose the basis for the concept of expanding the fuel balance in Russia through the development of CLCs and dividing the waste into suitable and unsuitable for energy use.

2. Materials and Methods

To achieve the goal we have done the following:

- Identified the existing principles for the formation of waste classifications in Russia and proposed a new approach to waste record-keeping to manage the choice of disposal technologies;
- Proposed principles for digitalization of waste generation and disposal monitoring, based on a new approach to waste record-keeping
- Evaluated the amount of electrical energy and heat and its share in energy consumption that could be obtained by using waste-to-energy technologies in several Russian cities.

2.1. Defining Existing Principles for the Formation of Waste Classifications in Russia and Proposing a New Approach to Waste Record-Keeping

In order to analyze the principles of waste classification in Russian practice and develop a new approach to waste record-keeping in a reviewed territory, we have:

- Examined regulatory documents and legal practice in waste management;
- Analyzed waste treatment technologies;
- Studied openly accessible information on waste generation. The study was supplemented by qualitative analysis of reports according to the form of regional schemes of waste management of all territorial subjects of the Russian Federation.

2.2. A New Approach to Waste Record-Keeping

In order to form new principles of digitalization of waste formation and utilization monitoring, we have:

- Studied information systems containing data on waste management in different countries;
- Analyzed design specifics of these information systems;
- Searched for missing parameters for applying these information systems toward determining waste energy use potential.

2.3. The Amount of Electrical Energy and Heat and Its Share in Energy Consumption That Could Be Obtained by Using Waste-To-Energy Technologies

For the evaluation, the following cities were chosen: Angarsk, Arzamas, Gay, Kirovsk, Kazan, Kashira, Murmansk, Novokuznetsk, Nazarovo, Ozersk, and Petrozavodsk. These cities have different populations and are situated in different Russian regions, so we were able to provide the calculations without the connection with local economic and climate conditions. Moreover, we had the most comprehensive data about their waste generation and energy consumption.

2.3.1. Theoretical Aspects

The amount of generated heat depends on the choice of technology of energy recycling of MSW. The greatest amount of heat can be generated by direct incineration; as such, a plant has the highest efficiency. However, it is possible to use the heat of direct incineration of solid waste either in the steam–power cycle (the Rankine cycle) or to produce heat energy in a boiler room. The use of waste gasification and pyrolysis products is also possible in gas turbine plants, binary cycle plants, and gas reciprocating machines.

It is also important to assess the energy potential of waste utilization by taking into consideration several factors:

- Waste, including municipal solid waste, is a local fuel, so it is necessary to use the waste at the place of generation (accumulation).
- The main advantage of municipal solid waste is that the place where it is generated directly coincides with the location of potential heat and electricity consumers. The haul distance includes collection of waste from waste containers and its delivery to the energy recycling facility.
- The limitations of the resource base consist in the range of the energy recycling facility and are usually confined to a settlement or a metropolitan area.
- The resource base is determined by the dynamics of waste generation in the territory under consideration.

In order to estimate the share of heat or electricity demand that can be met by energy recycling of waste, it is necessary to determine the chosen disposal technology, the resource base, and the heat of waste combustion. Since it is difficult to find information on the volume and composition of industrial waste, as such information is usually not published in Russia, in further estimates the research will be limited to municipal solid waste (MSW).

In order to calculate the amount of heat that can be generated by thermal processing of MSW, it is important to know, or estimate, the amount of waste generated annually and its thermophysical properties.

To assess the resource base of MSW, we introduce the thermal equivalent of MSW:

$$Q_{MSW} = J \cdot G_{MSW} \cdot Q_{MSW}^n \quad (1)$$

where Q_{MSW} is the thermal equivalent of MSW, kJ; J is the mass reduction coefficient reflecting the mass fraction of the components of MSW subject to energy recycling; Q_{MSW}^n is the net calorific value of MSW combustion, kJ/kg; and G_{MSW} is the annual mass of MSW generation in the territory under consideration, kg.

It should be noted that this definition of the thermal equivalent of MSW is valid for direct incineration of waste. In the case of pregasification, another coefficient m should be introduced, indicating the mass output ratio of generator gas from 1 kg of waste. Coefficient m depends on factors the method of gasification or pyrolysis and the type of a gasifying agent; it varies over a wide range and is determined according to the chosen technology. The value of should also be introduced for generator gas.

Knowing the morphological composition of waste or generator gas, the lower heat of combustion can be determined from the additivity concept of the components:

$$Q_w^l = \sum_{i=1}^n \frac{Q_i^n \cdot C_i}{100}, \quad (2)$$

where C_i is the mass fraction of the component in the composition.

Since the morphological composition of MSW is variable and diverse throughout the year, it is appropriate to use annual averages. If there are no reliable data on the morphological composition of MSW, it is possible to use the values taken from the experience of the incineration plant operation.

Within the framework of development of the heat supply scheme of Murmansk, the initial data were received from AO "Zavod TO TBO" (Joint Stock Company "Solid Waste Heat Treatment Plant", Russia, Murmansk) operating in Murmansk. Joint Stock Company "Solid Waste Heat Treatment Plant" is an enterprise of housing and utility complex.

The plant in Murmansk is designed for incineration of unsorted solid domestic waste from Murmansk, Kolsky, and Severomorsk Districts, and is equipped with two incinerator package boilers with steam capacity of 45 t/h each. In the process of thermal treatment of solid domestic waste, the enterprise generates cheap thermal energy, which it partially uses for its own needs, and partially sells through a steam collector for heating the city. The plant has two waste incinerators "CKD DUKLA" (CKD Group, a.s., Prague, Czech Republic) capable of incinerating up to 15 t/h of MSW. Additional fuel for stable combustion and kindling of boilers is fuel oil residue M 100 with a heat of combustion of 39,820 kJ/kg. Fuel and energy balance of the plant, according to the Joint Stock Company "Solid Waste Heat Treatment Plant" data (Heat supply scheme of Murmansk for the period 2019–2036, chapter 1, Table 155, https://www.citymurmansk.ru/strukturnye_podr?itemid=311, accessed on 23 August 2020), is given in Table 1.

Table 1. Fuel and energy balance of the incineration plant in Murmansk.

Indicator	Unit	2017	2018	2019
Consumption of fuel:				
Solid (MSW), actual fuel	t	63,480	65,236	74,909
Solid (MSW), reference fuel *	t.r.f.	12,696	13,047	14,982
Liquid (fuel oil residue), actual fuel	t	219	340.8	390
Liquid (fuel oil residue), reference fuel *	t.r.f.	298	463	530
Heat energy production	GJ	534,047	547,625	475,181
Heat supply to the heat network	GJ	357,126	351,700	305,427

* As a reference fuel, a hypothetical fuel with net calorific value equal to 29,308 kJ/kg (7000 kcal/kg) is mentioned.

According to the above fuel and energy balance, the calorific value of MSW ranges from 5000 to 9200 kJ/kg, with an average calorific value of 5860 kJ/kg.

To calculate the thermal equivalent of MSW, it is also necessary to evaluate the waste generation volumes in a selected territory. An experimental study should be conducted to determine the exact rate of waste accumulation. The methodology for calculating the value of the standard of MSW accumulation is described below.

2.3.2. Field Measurements

The mass and volume of municipal waste in a container is determined in the following order:

- A representative territory of the settlement, usually a residential block, with a known number of residents and a dedicated waste disposal site for the waste generated in the selected block, is selected;
- Waste is leveled (without compaction);
- The amount of waste collected is measured by a measuring bar;
- The weight of waste is determined by electronic scales. For example, crane scales OCS-1-SP with an accuracy of 0.5 kg and scales OCS-005-SP with an accuracy of 0.02 kg can be used.

To achieve correct results, the following principles should guide the experiment:

- To determine the actual accumulation of waste generated by the population, sites with the following number of residents are selected: in cities with a population of up to 300,000 people, sites are selected covering 2% of the total population for each type of building; in cities with a population of 300,000–500,000 people—1%; in cities with population over 500,000 people—0.5%.
- At least two typical public buildings for a given city are selected.
- Collection and measurement of waste exclude mixing of waste from various types of facilities, i.e., retail outlets, kindergartens, schools, or other organizations.
- All containers were completely cleaned before beginning measurements.
- When determining the standards for accumulation, the waste in containers is not compacted by service personnel.
- When determining the components of MSW, it is taken into consideration that the materials to be classified should be clean, and paper and textiles are dry.
- The experiment is conducted within one year (12 months) and measurements of waste volume and weight are taken daily during one week each season.

2.3.3. Calculation Part

The data obtained during the experiment are processed as follows:

1. Daily rate of accumulation per person by weight for a season.

The value of this indicator is determined by the formula:

$$G_{dw} = \frac{G_0}{n \cdot a}, \quad (3)$$

where G_{dw} is daily waste accumulation, kg/person day; G_0 is the weight of the waste to be removed from the site under study for the period of determining standards, kg; n is the number of residents, persons; a is the duration of determining accumulation standards, days.

2. The average annual daily rate of accumulation per person by weight.

The value of this indicator is determined by the formula:

$$G_{sw} = \frac{G_{dw}^{winter} + G_{dw}^{spring} + G_{dw}^{summer} + G_{dw}^{autumn}}{365} \quad (4)$$

where: G_{sw} is the calendar season average daily rate of accumulation, kg/person.

3. The annual rate of accumulation per person by weight.

The value of this indicator is determined by the formula:

$$G_{aw} = G_{dw} \cdot 365, \quad (5)$$

where G_{aw} is the annual rate of accumulation, kg/person.

The sampling of territories for waste-to-energy evaluation was based on the variability of waste generation and its volume. Having determined the resource base of MSW in the chosen cities, the estimation of quantity of thermal and electric energy that can be obtained by energy use of waste was made. The estimation was carried out for three cases:

1. Monogeneration of thermal energy by direct incineration (80% efficiency);
2. Monogeneration of electric energy in a steam power cycle (35% efficiency);
3. Cogeneration of heat and electric energy in a steam power cycle (generation of electric energy at the heat consumption of 0.201 MJ of electric energy per 1 MJ of thermal energy, the coefficient of fuel heat utilization (CFHU) is 0.8).

The results of the evaluation are presented in Table 4.

The average annual volume of MSW generation for energy use, allowing for the provisions of this study, was calculated by the formula:

$$G_{MSW}^{energy} = \frac{G_{aw} \cdot n \cdot Q_{MSW}^n}{\rho_{MSW} \cdot Q_{RF}^n}, \quad (6)$$

where G_{MSW}^{energy} is the average annual volume of MSW generation for energy use, tons of reference fuel; G_{aw} is the average annual MSW accumulation rate, kg/people per year; ρ_{MSW} is the density of MSW, kg/m³; and Q_{RF}^n is the net calorific value of reference fuel, equal to 29,308 kJ/kg (7000 kcal/kg).

3. Results and Discussion

3.1. Existing Principles for the Formation of Waste Classifications in Russia and a New Approach to Waste Record-Keeping

Some Russian regions provided data in accordance with the governmental order “On approval of requirements to the composition and content of territorial schemes and waste management, including municipal solid waste” (Russian Federation Government decree N 197, 16 March 2016 “Об утверждении требований к составу и содержанию территориальных схем обращения с отходами, в том числе с твердыми коммунальными отходами”); however, most reports do not include a number of important parameters. For example, the most detailed information is provided by the Republic of Ingushetia. In Tatarstan [25] and in Moscow [26], there is a lack of data on disposal, and the Novosibirsk Region has not provided data for each class of hazardous waste. The lack of electronic reporting standards complicates data analysis and makes it more difficult to combine companies into a single information system that effectively handles the existing disposal problem, including the use of this waste in the power industry. Such a system requires a clear classification of the waste generated. When analyzing the reports, we identified several classification criteria according to Russian legislation and state standards. Features of different types of classifications are given in Table 2.

Having analyzed the classifications, we can notice that most of them provide general information on waste. Classification according to GOST 30775-2001 “Resource saving. Waste management. Classification, identification, and codification of waste. Main provisions” contains the most information on waste management activities: place of origin, implemented method of waste management, reasons for conversion of material into waste. However, it does not indicate the recommended method of waste management. Moreover, the waste-to-energy conception is not considered there at all.

The distinguishing characteristic of our approach to the development of the resource base of the fuel and energy complex implies a clear system of evaluation of the potential for obtaining fuel resources from waste of different origin in a selected territory. A unified template should include such parameters as:

- Hazard class, amount of waste generated, treated, and used;
- Export capability, i.e., waste sent to other regions;
- Import capability, i.e., incoming waste from other organizations (regions);
- Amount (share) of waste that is technologically suitable for energy use.

Table 2. Features of different types of classifications.

Classification	Features of Classification
1. Hygienic classification according to SP 2.1.7.1386-03 “Sanitary regulations on determining hazard class of toxic wastes of production and consumption” (СП 2.1.7.1386-03 “Санитарные правила по определению класса опасности токсичных отходов производства и потребления”, 2011)	—Divides wastes by their toxic impact on the environment and human health—Must always be indicated in the hazard certificate of waste
2. Classification according to GOST 12.1.007-76 “Occupational safety standards system. Harmful substances. Classification and general safety requirements” (ГОСТ12.1.00776 “Система стандартов безопасности труда. Вредные вещества. Классификация и общие требования безопасности”, 1976)	—Divides wastes into hazard classes by the degree of impact on the organism—Exists to estimate the average lethal doses
3. Classification according to the requirements of Federal Law No. 89 “On production and consumption wastes” (article 4.1) (Russian Federal law N 89-ФЗ24.06.1998 “Об отходах производства и потребления”)	—Divides wastes into hazard classes by the degree of negative impact on the environment —The methodology of determining the hazard class does not allow for possible transformations of substances in the natural environment, under the influence of precipitation, sun, oxygen, etc.—The use of the classifier is mandatory
4. Classification according to the Federal Classificatory Catalogue of Wastes (FCCW) (Order of Russian Federal Service for supervision of natural resources management N242 22.05.2017 “Об утверждении Федерального классификационного каталога отходов”)	—For classification of wastes by types, allowing for structuring of information—Mostly needed just for statistics
5. Classification according to GOST 30775-2001 “Resource saving. Waste management. Classification, identification, and codification of waste. Main provisions” (ГОСТ30775-2001 “Ресурсосбережение. Обращение с отходами. Классификация, идентификация и кодирование отходов», 2001)	—The code contains all basic information about the waste —Specifies the place where the waste was generated and where it was sent —Specifies the implemented method of waste management
6. Classification of medical waste according to SanPiN 2.1.7.2790-10 “Sanitary and epidemiological requirements for medical waste management” (СанПиН2.1.7.2790-10 “Санитарно-эпидемиологические требования к обращению с медицинскими отходами”, 2010)	—Divides medical waste into hazard classes by toxicity, infectivity, and radioactivity
7. Classification of mercury waste according to GOST R 52105-2003 “Classification and methods of processing of mercury waste. Main provisions”.(ГОСТ P52105-2003 “Ресурсосбережение. Обращение с отходами. Классификация и методы переработки ртути содержащих отходов. Основные положения”, 2003)	—Divides wastes according to the mercury content —Is used to determine the method of processing mercury waste

It is necessary to determine the expediency of converting this information into the form of fuel and energy potential. Having an opportunity to identify the amount of resource suitable for conversion to energy from the point of view of the current development of scientific and technical progress, it is necessary to determine the criterion by which this quantity will be included into this database. Such a criterion may simply be the presence of a fuel shortage in the region (the most obvious option), but there may also be an economic criterion, which determines the comparative economic efficiency of replacing traditional fuel (gas, fuel oil residue, coal, diesel) with waste-to-energy usage, in other words, minimization of the fuel component of the commodity prime cost in case of the technological possibility of its use. This information should be generated not only on an annual basis, but also promptly, at least daily.

3.2. Principles for Digitalization of Waste Generation and Disposal Monitoring, Based on a New Approach to Waste Record-Keeping

An example of implementation of the data generation system is a mobile application. To increase the level of availability of information on MSW recycling, in a number of countries, several mobile applications have been created and are functioning, such as “Recycle Nation” (USA), “My-Waste” (international), “Recycle Right” (Australia), “We Recycle” (Great Britain). Recycle Nation (USA) is a navigation application designed to study the theory of recycling as well as to deepen knowledge in this field. In addition, the application is able to provide information on the status of recycling in the USA. The application also contains a database (considered one of the most comprehensive), which contains more than 2500 items. With this database, it is possible to find out whether a

product can be recycled. In addition to all of these advantages, the application is able to display a map of collection centers for electronic or clothing waste. Sorting waste using the Internet of Things is becoming more and more popular [27].

At present, in Russia, there is a database within the unified state information system EGIS UOIT [28]. It contains detailed data on licenses and technologies, a map of disposal and burial sites, and a databank on waste management, but this system is not updated and based on data that are contradictory according to different sources.

We suppose that the improvement of EGIS UOIT should imply determining the principles of digitalization of the system:

- Codes for garbage cans according to the hazard classes (e.g., the garbage can according to GOST 12917-78);
- Codes for garbage cans by types of waste, based on reading of which the waste should be automatically classified as suitable for energy use or other;
- Transfer of information to a logistics company, where the volume is recorded by means of an electronic document management system. If enterprises produce certain types of waste (for example, lumber enterprises), these data are immediately received by the Database Management System (DBMS) under the appropriate classifier and protocol. If it is not possible to accurately follow the waste classification, they enter the system as final data. If a company also recycles or disposes waste, the amount of recycled waste must also be recorded to monitor its utilization.

Hence, the system should be daily supplemented with new data and thus the promptness of data on waste turnover will be achieved.

If the data have already been entered into the classifier, recycling plants select the types of waste they need for the most efficient disposal. There are more than 200 recycling companies in Russia (as of 2018) [29].

It is important that the enterprises engaged in recycling will have to timely update the data on their technologies and describe their effectiveness, which will make it possible to promptly reveal the potential and to use the underused production facilities, including energy processing, and thus to develop new sources of alternative energy.

The assessment of the energy potential of waste allows quick control over changes in resource potential. For example, out of 77.1 million tons of MSW at certain recycling technologies and at average efficiency of a power plant of ~30%, we can obtain 25.16 million GJ, which is comparable with 702.12 million m³ of methane, 619.64 thousand tons of fuel oil residue, or 510.21 thousand tons of reference fuel [30,31].

The analysis of the global experience in waste management allowed identification of the main technologies used to implement CLCs using the most common types of waste (Table 3).

The data listed in the Table 3 can be used during decision-making on recycling technologies and be automatically suggested in the system (or digital application) as a method of processing a specific type of waste.

The list presented allows for drawing a conclusion about priorities of nonenergy recycling of paper and cardboard, and plastic products. Thus, the most common technologies for obtaining energy from waste have been identified: direct incineration, gasification, pyrolysis, methane fermentation in digesters, and landfill gas collection from landfills. Products of gasification and pyrolysis can be used as boiler fuel or for production of liquid fuel for internal combustion engines. The heat of combustion of waste or products of its processing can be used both in a cogeneration plant and in a monogeneration plant—to produce only heat or only electrical energy. Of course, cogeneration enables a much more efficient use of fuel heat compared to separate production of heat and electricity [51], but the decision to choose a particular technology should be made based on the context, depending on the needs of customers for a certain type of energy.

Table 3. Main directions of development of municipal solid waste recycling.

No.	Type of Waste	Recycling Technology	Output Raw Materials (Resource)
1.	Waste oils [32]	Pyrolysis	Gaseous and liquid hydrocarbons, pyrocarbon
2.	Mercury waste [33]	High-temperature firing, thermal vacuum technology	Processed mercury
3.	Rubber products (rubber tires, rubber bags)	Mechanical grinding [34] Regeneration [34] Incineration and pyrolysis [35]	Rubber granules Rubber with retained original structure Combustible gas mixtures (gas synthesis)
4.	Plastic products [36]	Mechanical grinding Method of destruction of plastic waste Method of remelting (granulation and pelletization method) Method of reprecipitation from solutions Method of chemical modification	Granules and powdered materials that are subjected to injection molding Oligomers and monomers (used to produce fiber and film) Granulate Powders (used for polymer coatings) Materials with new physical and chemical properties
5.	Electrical and electronic equipment [37]	Shredding of undismantled equipment and subsequent sorting of the resulting scrap	Polymetallic concentrate
6.	Medical waste (Class A and B) [38]	Pyrolysis, plasma gasification [39,40]	Depending on the composition of the waste recycled, it is possible to produce pyrolysis oil and industrial carbon
7.	Biological waste [41]	1. Disposal by heating the waste to 100–130 °C 2. Disposal using protein hydrolysis 3. Incineration 4. Methane fermentation	Production of meat and bone tannage, ground bone, blood tannage, fish tannage, and fat Production of biogas
8.	Municipal solid waste [42]	Shredding, separation, and dehydration of MSW Incineration, pyrolysis, gasification	Solid fuel Power generation
9.	Ashes and slags from solid fuel combustion [43]	Separate collection of ash and slag directly after incineration	Ash-and-slag waste mixture (used as additives in manufacture of construction materials and products)
10.	Food waste	Composting [44] Pyrolysis [45] Direct production of biogas [46]	Agricultural compost Environmentally friendly recycled hydrocarbon resources Biogas
11.	Paper and cardboard [47]	Turning into a fibrous state	Production of paper and cardboard
12.	Municipal liquid waste	Desilting Purification with sorbents [48] with further control of the purified water composition [49] Fermentation of sediment in digesters	Silt (solid sediment) Silt, used sorbent Methane, silt
13.	Wood waste [50]	Pyrolysis Gasification Hydrolysis Incineration	Alcohol, acetic acid, combustible gases, charcoal Combustible gas Ethyl alcohol, fodder yeast, furfural, turpentine Heat energy, electricity

3.3. The Amount of Electrical Energy and Heat and Its Share in Energy Consumption That Could Be Obtained by Using Waste-To-Energy Technologies in Several Russian Cities

The analysis of territorial schemes of waste management of the Russian Federation allows for drawing a conclusion that in the territory of Russia, the average density of MSW

is 190 kg/m³. Taking this density into consideration, the mass of MSW generated in the territories reviewed is further calculated.

The results of the electricity and heat generation estimates are given in the Table 4.

Table 4. Estimates of electricity and heat generation.

Settlement	G_{aw} , m ³ /ppl	n, 10 ³ ppl	G_{MSW}^{energy} , t.r.f.	W_{heat}^{mono} , GJ	W_{el}^{mono} , MWh	W_{heat}^{co} , GJ	W_{el}^{co} , MWh
Angarsk	1.56	226.4	13,416	314,552	38,227	260,133	17,580
Arzamas	1.80	104.5	7149	167,620	20,370	133,894	9368
Gay	1.43	35.2	1912	44,835	5449	35,814	2506
Kirovsk	1.88	25.9	1856	43,505	5287	34,752	2431
Kazan	1.94	1231.9	90,790	2,128,681	258,694	1,700,383	118,972
Kashira	1.72	49.2	3218	75,448	9169	60,268	4217
Murmansk	1.90	298.1	21,517	504,488	61,309	402,983	28,196
Novokuznetsk	1.30	552.4	27,284	639,696	77,741	510,987	35,753
Nazarovo	1.32	50.4	2527	59,254	7201	47,332	3312
Ozersk	1.67	79.5	5044	118,256	14,371	94,463	6609
Petrozavodsk	1.47	278.6	15,556	364,723	44,324	291,339	20,384

W_{heat}^{mono} heat monogeneration, W_{el}^{mono} electricity monogeneration, W_{heat}^{co} heat cogeneration, W_{el}^{co} electricity cogeneration.

Comparing calculated G_{MSW}^{energy} with the data of Eurostat (energy balance sheet, 2019 edition), it can be noticed that our results correlate well with energy generation from nonrenewable wastes for the European countries with population comparable to the Russian cities.

Figure 1 shows an analysis of the share of the area's demand for heat, which can be met by the energy recycling of MSW (direct incineration).

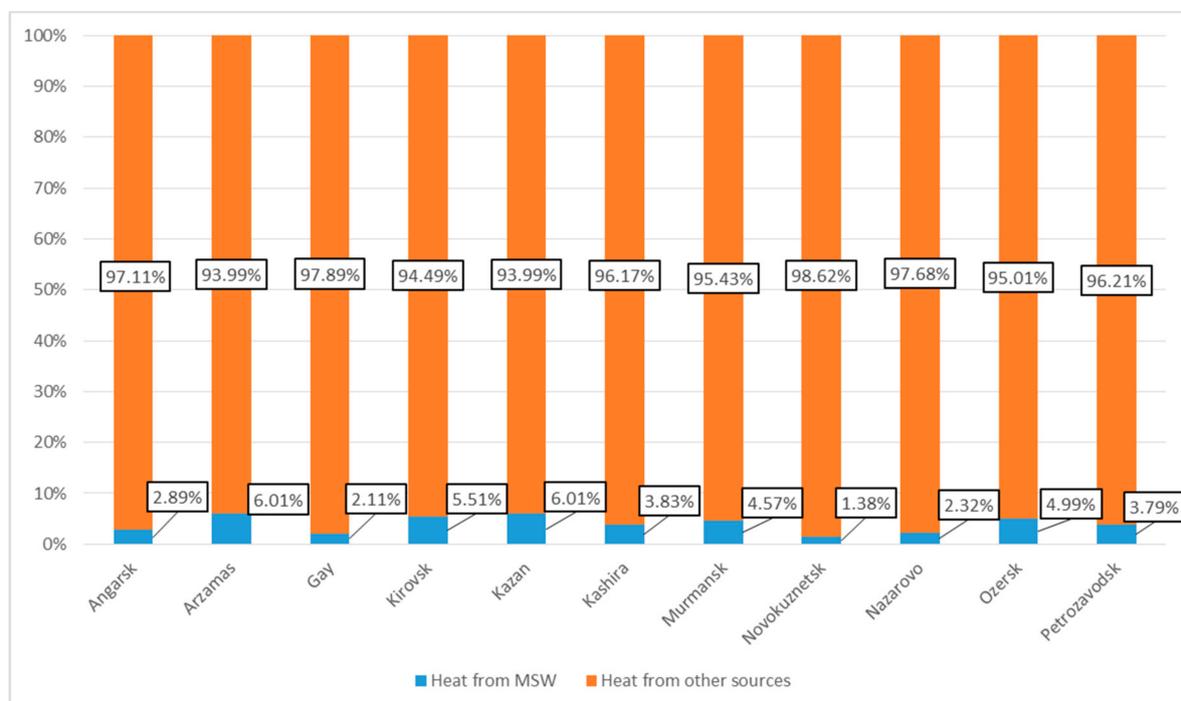


Figure 1. Percentage of heat demand that can be met by the energy recycling of MSW.

The results of the evaluation have shown that due to energy recycling, MSW can cover from 2.11% to 6.01% of the heat demand of the territory under consideration. Thus, when using MSW as a source of heat, it is relevant to speak about small (distributed) energy facilities, operating for the designated area.

3.4. Further Research Directions

At present in Russia, the data on waste are not gathered effectively and are not structured.

There is global experience in creating information systems, but it does not cover the fuel and energy balance in general.

To improve the current closed-loop resource cycle system, the role of energy recycling of waste should be increased.

After creating an information system for resource potential of waste, the energy sector will have more information about potential resources and will be able to define the strategy for technology development and get a new basis for the fuel and energy balance. Such a system becomes especially relevant in energy deficit regions.

The proposed approach can be useful also at the management level of CLCs of certain production complexes. An example of such complexes could be agricultural enterprises [52], timber processing, and other large industrial systems with constantly forming waste flow, which, for the most part, bring only cost indicators in the economy and should become a new raw material source for the energy system.

Creation of the resource potential information system will allow updating the regional fuel and energy balances by taking into account the possibilities of CLC implementation. Considering this, it is necessary to improve the methodological approach to formation and optimization of the fuel and energy balance.

The fuel and energy balance is a system of indicators reflecting the correspondence between the production and consumption of fuel and energy resources, their sources, and directions of their use. The fuel and energy balance is developed for the country as a whole, for the regions of the Russian Federation, for municipalities, for individual organizations, and for energy objects. There is a distinction between consolidated fuel and energy balances by individual types of fuel and energy resources (single-product balances), planned, and reporting balances. The process of planning and forecasting is carried out with the help of economic and mathematical modeling, which allows for prompt variation and calculation of processes and various parameters of energy production. The mathematical description is based on the equilibrium model of the energy producing and energy consuming sector of the national economy of the region in the form of systems of linear and nonlinear equations and inequalities, which describe the production, transformation, and consumption of energy resources and types of energy, as well as the associated price transformation of energy in the process of its production and consumption.

The fuel and energy balance is synthesized from seven single-product balances (balances of coal, other solid fuels, oil, oil products, gas, electricity, heat). We consider it necessary to distinguish a separate column “energy potential of waste” in the balance structure.

The structure of product balances, including municipal solid waste, (Equations (7)–(9)), on the basis of the compiled summary table of fuel and energy balance, is described by the following general scheme (applied in Russian practice and corresponding to international standards):

1. Resource part:

$$R_i = X_i + I_i + \Delta Z_i + P_{xi} + G_{MSW}^{energy} \quad (7)$$

where i is the index used for product type; R_i is the available volume of products of type i ; X_i is the volume of output (production) of products of type i ; I_i is the import of products of type i ; ΔZ_i is the stock change of products of type i ; and P_{xi} is the losses of products of type i at the stage of production.

2. Areas of use:

$$IR_i = E_i + VI_i, \quad (8)$$

$$VII = (PREi + PERsti) + (Snti + Mnti) + TEi + Ptri \quad (9)$$

where IRi is the volume of used products of type i ; Ei is the export of products of type i ; VII is the internal use of products of type i ; $PREi$ is the volume of products of type i aimed at conversion to other types of energy (electricity and heat); $PERsti$ is the volume of products of type i aimed at processing as raw materials into other fuels; $Snti$ is the use of products of type i as a raw material for the production of nonfuel products; $Mnti$ is the use of products of type i as a material for nonfuel purposes; TEi is the use of products of type i directly as fuel or energy (not for conversion into other types of energy and not as raw materials for processing into other types of fuel); and $Ptri$ is losses during distribution of products of type i (energy transmission and transportation of fuel products).

The criteria of optimality can be both maximization of profit or minimization of costs, and maximization of use of resource potential of a region. We consider the criterion of maximum involvement of waste in the fuel and energy balance more promising. A relevant method of optimization search is the use of a genetic algorithm, as this method is especially effective when taking into consideration nonlinear limitations of real tasks.

The basic provisions of the foundations of “new industrialization” and “technologies of the VI technological mode” are being developed now as new directions for the development of future technologies. The task of creating a new raw material base requires new technologies and new economic solutions, and can lead to the overall modernization of the Russian economy.

4. Conclusions

1. The current waste classification principles in Russia largely take into account the degree of its toxic effects on habitat and human health. A new approach to waste management is proposed to manage the choice of recycling technologies, based on the division of waste into suitable for energy use and other.
2. On the basis of the new waste accounting criterion, the following principles are proposed for the digitization of waste management monitoring: the speed of data access to the monitoring system must be facilitated by defining the codes for waste containers based on waste types; the transfer information to a logistics company, where the volume is recorded through the electronic document system; and translation of that information into fuel and energy potential. A single template for an information system should include such options as:
 - Danger class, amount of waste formed, processed, and used;
 - Import capability, i.e., waste from other organizations (regions);
 - Export capability, i.e., the amount of waste disposed, buried, and shipped to other regions;
 - The amount (share) of waste that is technologically suitable for energy use.
3. The results of the evaluation show that due to energy recycling, MSW can cover from 2.11% to 6.01% of the heat demand.
4. The regional office for technological development of the CLC should use a mechanism for assessing the resource base using the new concept of “thermal equivalent of waste”. The thermal equivalent should be calculated only for the waste that is suitable for energy use.

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