Analysis of Energy Efficiency of Municipal Solid Waste Usage for Thermal and Electrical Energy Production

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Abstract. This work presents a review of ecological map of Leningrad Oblast' basing on established normative documents. It was established that the ratio of treated and utilized waste does not exceed 5-10% of the total material amount. This states for low degree of municipal solid waste (MSW) recycling. We have carried out analysis and selection of the priority way for MSW recycling. It was shown that usage of MSW as a fuel for thermal and electrical energy production economizes traditional fuel types (coal, gas, mazut). Also it serves for reduction of greenhouse gas emission. It was established that the most perspective method for thermal utilization is waste gasification. According to the world data, the efficiency for syngas production from gasification is about 70%. At this, the remaining portions are physical heat losses as well as chemical and physical energies of the generated tar. Gasification setup modeling was performed using Aspens Plus. The total efficiency of thermal and electrical energy production was 70.5%.

1. Introduction

Nowadays the problem of ecology in the Russian Federation has acquired particular urgency. The modern environmental issues include, but not limited to energy-saving and resource-saving technologies, waste and wastewater treatment [1-15]. Every year the amount of the collected industrial and household waste increases, while efficient recycling methods are rarely used [16-25]. The total annual amount of municipal solid waste (MSW) in our country is about 7 billion tons, however only a small part of it is recycled. The major part of waste is buried, disposed in illegal dumps or burned, though it contain a significant amount of secondary energy resources, which might be efficiently recycled or reused.

About 80-100 bln tons of solid waste (domestic waste, worn tires, metallurgical production slag, concentration plant waste, etc) is now stored within the territory of the Russian Federation. The existing level of waste recycling in RF is very low, for example: recycling for MSW is 5-10%, for worn tires it is 5-7%, for metal scrap it is 20-30%, for building waste it is 10-35%. All unprocessed waste is send at numerous landfills and dumps. Every year about a hundred hectare of land suitable for housing and agriculture are disposed for MSW burial [26-32].
2. Estimation of Ecological Map of the Leningrad Oblast’

Territorial schemes of various waste types (including municipal solid waste) treatment are now developing in the Russian Federation. From the year 2016 in Leningrad Oblast' the Act №7 of the Leningrad Oblast' Department for management and control of waste treatment is valid [33].

This document is a territorial scheme for waste treatment, which was developed according to the Article 13.3 of the Federal Law of June, 24 1998 No. 89-FZ "About production and consumption of wastes" and Requirements to composition and content of territorial schemes for waste treatment, including municipal solid waste, accepted by the Russian Federation Government Resolution of March, 16 2016 No. 197 aiming at organization and implementation of activities for transportation, treatment, utilization, neutralization, burial of wastes at the Leningrad Oblast' territory.

At this, now the targeted indicators for utilization, neutralization and disposal of waste are not fixed legislatively at Leningrad Oblast'. According to Appendices 3 and 10 [33] 1070 thousands tons of waste are produced annually in Saint-Petersburg, at the same for the rest part of Leningrad Oblast' this value is 495 thousands tons. It should be noted that at Lomonosovskiy, Volosovskiy and Kirovskiy districts waste disposal sites are absent, or its' residual capacitias are lower than annual volume of MSW production.

The Appendix 12 [33] shows the balance of quantitative characteristics of production, treatment, utilization, neutralization and disposal of municipal solid wastes. Tables 1 and 2 present these values.

Table 1. The balance of quantitative characteristics of production, treatment, utilization, neutralization and disposal of municipal solid wastes.

| Waste type                                      | Amount of produced waste, tons/year | Amount of treated waste, tons/year | Amount of utilized waste, tons/year | Amount of neutralized waste, tons/year | Amount of disposed waste, tons/year |
|------------------------------------------------|-------------------------------------|-----------------------------------|------------------------------------|--------------------------------------|-----------------------------------|
| Unsorted household waste (excluding large-size) | 391064.329                          | 71246.155                         | 7124.616                           | 0.000                                | 383939.714                        |
| Large-size household waste                      | 28456.314                           | 5531.356                          | 553.136                            | 0.000                                | 27903.178                         |
| Unsorted waste from office and amenity spaces of organizations (excluding large-size) | 26585.151                           | 4810.234                          | 481.023                            | 259.735                              | 25844.393                         |
| Sweepings and other waste from enterprise and organization territory cleaning | 19781.896                           | 1318.148                          | 9282.316                           | 0.000                                | 10499.580                         |
| Other MSW                                       | 29514.512                           | 2114.277                          | 326.250                            | 1.795                                | 29186.467                         |
| Total                                           | 495402.201                          | 85020.170                         | 17441.091                          | 261.530                              | 477699.580/1547699.580*           |

Table 2. The balance of quantitative characteristics of production, treatment, utilization, neutralization and disposal of municipal solid wastes and similar to them according to the hazard classification.

| Waste type                                      | Class of hazard | Amount of produced waste, tons/year | Amount of treated waste, tons/year | Amount of utilized waste, tons/year | Amount of neutralized waste, tons/year | Amount of disposed waste, tons/year |
|------------------------------------------------|-----------------|-------------------------------------|-----------------------------------|------------------------------------|--------------------------------------|-----------------------------------|
| Municipal solid waste and similar to them       | IV              | 445881.863                          | 77786.494                         | 8489.575                           | 259.735                             | 437132.352                        |
|                                                 | V               | 49520.538                           | 7233.676                          | 8951.516                           | 1.795                               | 40567.228                         |
| Total                                           |                 | 495402.201                          | 85020.170                         | 17441.091                          | 261.530                             | 477699.580/1547699.580*           |

* is for disposed municipal solid waste of the Leningrad Oblast'/total amount of disposed taking into account waste from other RF territorial subjects (Saint-Petersburg).

According to the data from tables 1-2, the ratio of treated and utilized waste does not exceed 5-10% of the total material amount. This states for low degree of MSW recycling. Thus, search for solutions for efficient waste utilization is one of the key ecological tasks at the Leningrad Oblast'.
3. The Choice for Priority Way of MSW Recycling

There are a vast amount of methods for waste processing. These methods are often divided into two major groups: thermal and non-thermal. Non-thermal methods include burial, composting and recycling. Thermal methods stand for high-temperature treatment of MSW (burning, pyrolysis, gasification), at this liquid phase-water-is always evaporated, solid phase of the inorganic substance undergoes structural transformations: dehydration, dissociation, polymorphisation, melting, evaporation.

Nowadays burning of waste is one of the most widespread methods for its' utilization. Despite inhomogeneity of municipal solid waste content, it may be considered as a low-grade fuel. The lowest combustion heat per working mass for Leningrad Oblast’ wastes is about 7500-8000 kJ/kg, humidity is about 30-40%, ash content is 25-30% [34].

Usage of MSW as a fuel for thermal and electrical energy production as opposed to its burial economizes traditional fuel types (coal, gas, mazut). Also it serves for reduction of greenhouse gas emission. At this, the most perspective method for thermal utilization is waste gasification.

Gasification of the organic waste is a method for transformation of liquid or solid fuel into the combustion gases by means of incomplete air (oxygen, water vapor) oxidation at high temperature with possible application of catalysts and outside warming, which is essential for autothermal or non-autothermal process running. The advantages and disadvantages of the above-described utilization method are presented in Table 3.

Table 3. The advantages and disadvantages of MSW gasification.

| Advantages                                                                 | Disadvantages                                      |
|---------------------------------------------------------------------------|----------------------------------------------------|
| The possibility of absence of MSW preliminary preparation                 | Low utilization if RF                               |
| The absence of severe requirements for MSW content.                       | The necessity for usage of equipment for syngas purification. |
| Synthesis of the secondary fuel.                                          | Problems with ash burial.                          |
| Easy usage of secondary fuel.                                             | Low efficiency of black metal recovery from slag.  |
| Ability for change of combustion heat of the end product.                 |                                                   |
| Relatively low costs for the process implementation.                      |                                                   |
| High energy efficiency (up to 95%).                                      |                                                   |
| Low linear velocities of the gas flow in reactor and its filtration       |                                                   |
| through a layer of initial processed material result in extremely low     |                                                   |
| outflow of the dust particles with syngas.                                |                                                   |
| Syngas is easier for cleaning than flue gases due to low temperature,     | Valuable component loss in slag.                   |
| smaller volume and higher pollutant concentration.                       |                                                   |
| The partial decomposition of the nitrogen-containing organic compounds at |                                                   |
| oxygen-free environment, which results in lower amount of nitrogen oxides|                                                   |
| in flue gases.                                                           |                                                   |
| Two-stage combustion allows one to drastically reduce dioxines formation. |                                                   |
| Ash from reactor has low temperature.                                     |                                                   |

There are about 200 various plants with pyrolysis/gasification technologies worldwide. These plants are widespread in Japan, Germany, Norway, Great Britain, to the less extent in France, Austria, Denmark, Switzerland. Unfortunately, there are no such plants nowadays in Russia.

The issue under investigation is of immediate interest for every large and medium settlements. For this matter European countries have more rich experience than the Russian Federation. For example, in Estonia environmentally sound management of waste is in progress from 2010. The laws in this area are applicable for both regional and federal levels. Its basic ground is prevention of environment pollution, which is referred to all manufacturing objects in the country. This includes ecological monitoring, estimation of negative impact on the environment, hazardous effluents control, inclusion of waste processing expenses into the bare cost of the product, etc. Waste recycling is under consideration, as well as secondary materials usage and energy recovery from waste [35].

At the same time MSW gasification technology finds its application at low-capacity installations. In Portugal the installations with productivity up to 100 kg/h are successfully used with 750 – 850 °C temperature maintaining at pseudo-fluidized layer [36-38]. In simplified form this system consists of raw material unit, reactor, cooling and gas purification unit (figure 1).
Figure 1. MSW gasification installation with productivity up to 100 kg/h.

Energy balance for this installation at air blow-off is presented in figure 2. In terms of MSW potential, the efficiency of syngas production installation is about 70%. At this, the remaining portion are physical heat losses as well as chemical and physical energies of the generated tar.

Figure 2. Energy balance of MSW gasification installation with productivity up to 100 kg/h [36].

4. Modeling of MSW Gasification Process

In order to estimate theoretical potential of MSW gasification products we performed modeling using Aspen Plus. This software is one of the basic instruments which is used for similar problems solving in Russian and world science [39-42].

Figure 3 presents the modeled MSW gasification scheme using Aspen Plus. The scheme includes solid fuel thermal conversion unit with separation of technological zones for pyrolysis and gasification, air compressor, combustion chamber for the obtained syngas, gas turbine, waste heat boiler and separators. The detailed information about the elements is given in Table 4.

Basing on the normative documents for institutions [43], the amount of the produced MSW at SPbPU is 270 m³/month. The preliminary calculations show that this waste amount is sufficient for production of 12-15 kW electrical energy. However, the existing typical size of both Russian and
foreign gasifiers, as well as generating installations (gas turbine installation, gas powered electrical generator) involves the use of equipment with unit power not less than 60 kW [44, 45].

Thus, this work presents simulation of MSW gasification for an installation with generated power of 100 kW (excluding capacity of supply equipment drivers of gas turbine installation). It is assumed, that during this project implementation the installation might use as raw materials not only the University wastes, but household wastes of the nearby residential quarter. Morphological and elemental composition of the initial fuel is taken from [45, 46].

![MSW gasification installation in the Aspen Plus.](image)

**Figure 3.** MSW gasification installation in the Aspen Plus.

| No. | Legend | Name | Functionality |
|-----|--------|------|---------------|
| 1   | PYROLYS| Thermal conversion reactor (pyrolysis zone) | Pyrolysis of the initial fuel, MSW elemental analysis recalculation in terms of convertible gas components. |
| 2   | GASIFIER| Thermal conversion reactor (gasification zone) | Calculation of equilibrium gasification process basing on minimization of difference between reaction Gibbs energies. |
| 3   | SEPSG | Syngas separator | Separation of solid and gas phases. |
| 4   | COMPR | Air compressor | Air compression for supply into the gasifier and for combustion at gas turbine installation. As a matter of calculation convenience, we combined air compressor of the gasifier and gas turbine installation in a single element. |
| 5   | AIRSPLIT | Air separator | Separation of air flows according to functions. |
| 6   | BURNER | Combustion chamber | Calculation of equilibrium syngas combustion process basing on minimization of difference between reaction Gibbs energies. |
| 7   | TURBINE | Gas turbine | Usage of thermal potential of flue gases for electrical energy generation. |
| 8   | HEATER | Boiler | Heating of return network water for consumer supply. |

The major energy indicators of installation operation are generation of electrical and thermal energy. The flows TURBWORK and COMPWORK account for electrical energy indicators on the scheme. At this, the useful production is determined by the difference between mechanical capacity of the turbine and compressor equipment. According to the calculation results, the useful capacity of the installation is 102 kW.

The typical network water heating amount for the network heater (HEATER) is 2.5 tons/h at peak mode from 70 °C to 130 °C. The temperature of the exhausted flue gases is 159 °C. Then the calculated thermal capacity of the network heater is equal to 203 kW at designed area of 0.7 m² and
average temperature pressure 337 °C. Table 5 presents basic calculated energy indicators for the MSW gasification installation.

**Table 5.** Calculated energy indicators of MSW gasification installation.

| No. | Characteristics                                               | Measurement unit | Value  |
|-----|--------------------------------------------------------------|------------------|--------|
| 1   | Electrical capacity of gas turbine installation              | kW               | 102    |
| 2   | Annual amount of nominal power operating hours               | h                | 7500   |
| 3   | Annual electrical energy generation                          | kW·h/year        | 765000 |
| 4   | Thermal capacity of the network heater                       | kW               | 203    |
| 5   | MSW consumption (at combustion heat per dry weight 15.58 MJ/kg) | kg/h             | 100    |
| 6   | Electrical efficiency of the installation                    | %                | 23.6   |
| 7   | Thermal efficiency of the installation                       | %                | 46.9   |
| 8   | Total efficiency of the installation                         | %                | 70.5   |

Consequently, the total efficiency of thermal and electrical energy production is 70.5%. This value is correlated with indicators of energy installations, which operate on alternative local solid fuel (wood, peat, etc). However, the obvious advantages of the presented development are usage of fuel with zero or “negative” price, and improvement of ecological environment in the city.

5. **Conclusions**

This work presents an analysis of energy efficiency of municipal solid waste usage for generation of thermal and electrical energies. The main conclusions are the following:

- The existing level of waste recycling in Russia is very low, for example: recycling for MSW is 5-10%, for worn tires it is 5-7%, for metal scrap it is 20-30%, for building waste it is 10-35%.
- Usage of MSW as a fuel for thermal and electrical energies production by means of gasification economizes traditional fuel types (coal, gas, mazut). Also it serves for reduction of greenhouse gas emission.
- The amount of MSW at SPbPU is 270 m$^3$/month. The preliminary calculations show that this waste amount is sufficient for production of 12-15 kW electrical energy.
- The calculated efficiency for production of thermal and electrical energies for MSW gasification installation in a cycle with gas turbine installation and boiler is 70.5%.

6. **References**

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