Comparative life cycle assessment of mini combined heat and power plants

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Abstract. The article presents the results of an environmental study of the mini combined heat and power plants (mini-CHPs) life cycle with gas engines operating on natural gas and biogas, and with diesel engines. The calculation of material and energy flows, the environmental impact on the atmospheric air, water basin and soil has been carried out. The largest mass of harmful substances in wastewater has been observed with the account of the life cycle assessment (LCA) for the mini-CHPs in biogas, the smallest mass - in diesel mini-CHPs. During the operation of biogas, gas piston and diesel PI, significant greenhouse gas emissions have taken place because of the fuel combustion. The article considers the issues of thermal pollution in the environment. It has been revealed that the life cycle of the bioenergy installations has a maximum impact on the environment, with the account of the fuel combustion in mini-CHPs with diesel engines. Biogas mini-CHPs have a greater advantage considering the processes of the operation and fuel combustion. The conducted research can help in choosing the type of the engine when designing a mini-CHP.

1 Introduction

The doctrine of the energy security of the Russian Federation provides for the development of distributed electrical energy generation, energy-saving and energy-efficient technologies [1]. Limiting the negative impact on the environment and ensuring the environmental safety of the economic activities of the fuel and energy complex organizations is crucial for the implementation of climate policy and accelerated transition to a "green economy".

The use of mini combined heat and power plants (mini-CHPs) [2] is very promising for the energy supply of the cities and objects remote from the energy supplying organizations: mining industry, munitions, industrial enterprises, housing and utilities facilities, agriculture resorts, boarding houses, rest homes, etc. The largest number of mini-CHPs is used in the extractive industries of the fuel and energy complex (FEC), f because of a large distance of facilities from the power systems, high expenses for laying power lines in Northern regions and their possible damage. Mini-CHPs can be constructed in industrial enterprises as the main, additional or backup source of electricity.

The combined production of heat and electricity at mini-CHPs contributes to a more environmentally friendly use of fuel compared with a separate generation of electricity and thermal energy at boilers that provides an ecological improvement of the environment.

The main advantages of mini-CHPs are the following: a low cost of generated heat and electricity, a significant reduction in losses of electrical and heat energy thanks to their closer distance to consumers, the

autonomy of operation, an increased reliability of heat supply, the possibility of rapid construction (up to a year), a fast payback, a low consumption of fuel, a wide range of different types of fuel, an environmental safety. At present, the electrical efficiency reaches 40%, and the heat efficiency - 50%, i.e., their full efficiency is within 80–90%, which is even higher than with the large CHP plants.

The choice of the type, power and quantity of power units at the mini-CHPs is determined by a large number of factors: reliability requirements, fuel availability, climatic zone, type of interfacing with power grids, consumer operation modes, etc. Gas piston units have the best performance for mini-CHPs power from 100 kW to 4 MW, and for the higher power - gas turbine. Diesel engines are recommended for non-gasified areas.

Natural gas and diesel fuel are used as fuel for the mini-CHPs. In addition, biogas can be used as fuel, which can be obtained from livestock waste [3]. The advantages of using bio-fuel include cost savings in wastewater treatment plants and reducing greenhouse gas emissions [4].

The expediency of selecting the type of engine for driving a mini-CHP generator is determined by technical, economic and environmental factors. In some cases, environmental criteria may be decisive. A full environmental assessment is possible using the life cycle assessment method (LCA).

The life cycle of any product includes a number of stages that start from the extraction of natural resources and end with the disposal of the equipment in the environment. The LCA method can help identify the peculiarities of the environmental problems and the

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possibility of improving the environmental aspects of products at various points in their life cycle [5].

The purpose of this work was to assess the life cycle of mini-CHPs with the gas piston engines (on natural gas and biogas) and with the diesel engines.

2 Life cycle assessment of mini-CHPs

The list of materials that make up the power installations (PI), and their mass (table 1) are the initial data for the environmental assessment. The mass of the components of the power installation parts has been determined due to the technical characteristics of the manufacturer.

Table 1. Masses of materials that make up the PI, and fuel.

Material	Mass of PI materials, kg		
	Biogas	Gas piston	Diesel
Steel	13416	1514	1383
Cast iron	2856	2856	2608
Copper	150	150	137
Aluminum	408	408	373
Total	16830	4928	4501
Fuel	329.4 thous. m ³	341.6 thous. m ³	239148 kg

To develop the life cycle, the following facilities, which the energy sources are composed of, have been considered: engine (steel, cast iron, aluminum); generator (steel, copper); container (steel).

The processes of extraction and production of fuel - natural gas and diesel fuel were also taken into account. Fuel consumption has been calculated for a year of operation.

The life cycle was divided into the following individual processes, based on the used materials and industries: mining of minerals (iron ore, copper ore, bauxites, gas, oil); production of materials (cast iron, steel, copper, aluminum, diesel fuel); production of energy sources; recycling process (cast iron, steel, copper, aluminum).

The mini - CHPs with the capacity of about 100 kW have been chosen for LCA. Biogas PI consists of a biogas installation operating on manure from a livestock, and a gas piston mini-CHP operating on biogas. The technical characteristics of PI [6] are presented in Table 2.

The following areas of exposure have been

considered for LCA: material flow - the consumption of natural resources and water, the territory alienation; energy flow – the input energy flows are included. The study takes into account only the power consumption; the environmental impact – the input flows are included, based on the types of used materials and industries. The discharge of wastewater, the emission of harmful substances into the air, the generation of waste, the emission of greenhouse gases, and thermal pollution have been taken into account in the study

2.1 Analysis of the material flow of the life cycle of mini-CHPs

To accommodate the mini-CHPs it is necessary to alienate the lands of a certain area, which depends on the type and capacity of the station. The areas of the mini-CHPs are presented in Table 3.

For the production and operation of the mini-CHPs, it is crucial to use natural resources, such as non-renewable natural resources - metal ores and fossil fuels, renewable natural resources - manure, as raw material for the biogas production. The calculation of the natural resources consumption is based on the mass of materials used for the production of EC and specific values of the waste generation [7] at all stages of the life cycle. The results of the natural resources calculation consumption are given in Table 3. For the fuel, the initial data were the volume of natural gas (thous. m³) and the mass of diesel fuel (tons) burned a year.

Water consumption takes place at all stages of the power plants life cycle. The quantity and quality of used water depends on the type of industry, technology and raw materials. Water in industrial water supply systems is applied to cool equipment; it is used as a medium that absorbs and transports impurities, and as a solvent for reagents. The calculation of water consumption for the production of PI has been made according to the specific water consumption norms in technological operations [8].

The rate of water disposal is determined by the rate of water consumption and water losses in the process of its use in accordance with the adopted scheme of water supply production. When establishing the norms for water disposal, the following factors are taken into account: the expediency of extracting and using valuable impurities contained in wastewater, the necessary degree of purification of wastewater from contamination, the

Table 2. Mass of materials that make up the PI and fuel.

PI type	Biogas	Gas piston	Diesel
Engine type	Caterpillar G3406 (DM8660)	Caterpillar G3406 (DM5447)	D266.4 Minsk Motor Plant
Fuel	Biogas	Natural gas	Diesel
Electric power, kW	103	125	100
Fuel consumption	37.6 nm ³ /h	39.0 nm ³ /h	27.3 kg/h
Mass, kg	4082	4928	4500
Biogas installation BIOEN-1	Bioreactor capacity 100 m ³	-	-
Full weight, kg	16830	4928	4500

requirements for industrial water with the applied water supply system. The calculation of wastewater discharge for the production of PI has been carried out in accordance with the specific standards for technological operations. The results of the calculation of water consumption and drainage during the life cycle of power plants are shown in Table 3.

2.2 Analysis of the energy flow of the life cycle of mini-CH

Electricity consumption takes place at all stages of the life cycle: mining, ferrous and nonferrous metallurgy, engineering and disposal of waste. The calculation of electricity consumption is based on the mass of the constituent materials of the power plant and the specific consumption of electrical energy [9]. The results of the calculation of the power consumption at the stages of the PI life cycle are given in Table 3.

2.3 Analysis of the ecological flow of the mini-CHP life cycle

2.3.1 Pollution of the water basin

The toxicity of wastewater production processes has been determined by the conditional mass of contaminated impurities based on the relative hazard of the harmful substances discharge into the reservoir and the total mass of harmful substances. The relative aggressiveness of the pollutant depends on the maximum permissible concentration (MPC) of the substance. The calculation results of the conditional mass of harmful substances during the life cycle of power plants are shown in Table 3.

2.3.2 Air pollution

The process of mining and production processes are accompanied with an emission of toxic substances into the air. The calculation of the reduced mass of harmful substances has been made on the basis of the specific emissions and maximum permissible concentration (MPC) values. The volume and concentration of pollutants in the flue gases of the mini-CHPs have been calculated in accordance with the technical characteristics of the engines [10, 11].

The reduced mass (M) of the annual emission of harmful substances into the atmosphere is determined by [12]:

$$M = \sum_{i=1}^N A_i \cdot m_i \quad (1)$$

where t_i - is the mass of the annual emission of an impurity of the i -th species into the atmosphere, t/year; A_i - is an indicator of the relative aggressiveness of an admixture of the i -th species, t/t; N - is the total number of impurities emitted by the source into the atmosphere.

The value of A_i is determined by the formula:

$$A_i = a_i \cdot \alpha_i \cdot \delta_i \quad (2)$$

where a_i - is an indicator of the relative danger of impurities in the air breathed by a person; α_i - is an amendment that takes into account the probability of accumulation of the initial impurity or secondary pollutants in the environmental components and in the food chains, as well as the impurity entering the human body in a non-inhalative way; δ_i - is an amendment that takes into account the effect on various recipients other than man.

The numerical value of the indicator a_i is determined by the formula:

$$a_i = \sqrt{\frac{MPC_{ad.CO} \cdot MPC_{w.z.CO}}{MPC_{adi} \cdot MPC_{w.z.i}}} \quad (3)$$

where $MPC_{ad.i}$ - is the average daily MPC of the i -th impurity in the atmosphere; $MPC_{w.z.i}$ - MPC of the i -th impurity in the air of the working zone; $MPC_{ad.CO}$ - the average daily MPC of carbon monoxide in the atmosphere of the populated areas; $MPC_{w.z.CO}$ - MPC CO in the air of the working zone.

The value of the amendment a_i is assumed to be: 5 for toxic metals and their oxides - manganese, nickel, chromium, zinc, arsenic, cadmium, mercury, lead; 2 for other metals and their oxides; 1 - for all other pollutants emitted into the atmosphere (for gases, acids and alkalis in aerosols, etc.).

The value of the amendment δ_i is assumed to be: 2 - for hydrogen fluoride, molecular fluorine, sulfur dioxide, hydrogen sulfide; 1.5 - for nitrogen oxides, carbon disulfide, highly soluble inorganic fluorine compounds; 1.2 - for non-toxic metals and their oxides (sodium, magnesium, potassium, calcium, iron), ammonia, inorganic silicon compounds; 1 - for other compounds and impurities (for carbon monoxide, light hydrocarbons, toxic metals and their oxides, etc.).

The results of the calculation of the reduced mass of pollutants with the account of the combustion of fuel are presented in Table 3.

2.3.3 Emission of greenhouse gases

The emission of greenhouse gases occurs at almost all stages of the power plants life cycles. The emission of greenhouse gases takes place during the extraction of oil and gas, at the enterprises of ferrous and nonferrous metallurgy. During the operation of biogas, gas piston and diesel PI, significant greenhouse gas emissions occur because of the fuel combustion. The initial data for calculating greenhouse gas emissions are the masses of materials at each life cycle stage and specific greenhouse gas emission factors, and for the operation process the volume and type of the burned fuel [10, 11]. The results of the study of total emissions for all PI types are presented in Table 3.

2.3.4 Soil contamination

Waste generation happens at all stages of the life cycle and depends on the type of materials production and applied technologies. The mass of the generated waste has been calculated from the values of waste generation indicators for a specific production [3] and the mass of materials for each life cycle stage. The reduced mass of waste has been determined with the account of the indicators of the component hazard degree of the waste. Table 3 shows the calculation results.

2.3.4 Thermal pollution

Thermal pollution is characterized by an increase in the temperature above the natural level. Considering the fact that modern thermal power plants have an efficiency of no more than 40%, the inevitable heat loss during power generation will be up to 60%. This warmth "heats" the atmosphere and hydrosphere. In addition, it should be noted that a significant part of the generated electricity is ultimately converted back to heat in electrical heating and technological installations, lighting fixtures and is also dispersed into the environment. Studies of thermal pollution of the environment have been conducted on the basis of power, efficiency, consumption and calorific value of the fuel. Table 3 shows the calculation results.

3 Analysis of LCA mini-CHP results

Table 3 summarizes the results of the mini-CHP life cycle assessment.

The analysis of the results has enabled to make the conclusion that the worst environmental indicators are characterized by biogas mini-CHPs, which have the maximum mass of natural resources, station areas, waste masses, water consumption and discharge, the conditional mass of harmful substances in wastewater and emitted into the atmosphere due to the greater mass,

which includes a plant for the biogas production. For the mini-CHPs with the gas piston and diesel engine, these figures are significantly lower. The maximum contribution to LCA is made by the PI production stage.

The environmental impact of the thermal pollution may be assessed as very weak, and the scale - a pointed one.

With the account of the burning fuel process, the diesel mini-CHPs have the worst performance, while the biogas ones only emit harmful substances and greenhouse gases into the air. LCA fuel in all environmental parameters is several times higher than the life span of the power plants themselves; therefore, in case of raw materials, the biogas mini-CHPs have greater advantages.

4 Conclusions

The LCA of a mini-CHP has been assessed, which allows for an environmental comparison of various energy sources at all stages from mining, production of power plants, to the stage of generating electricity and recycling used equipment, taking into account the used fuel.

The environmental impact assessment has been carried out in the following areas: consumption of natural resources, territory alienation, waste generation, water consumption and discharge, emissions of harmful substances into the atmospheric air, greenhouse gas emissions, thermal pollution, power consumption.

The analysis of the results has allowed making the conclusion that the worst environmental indicators are characterized by the biogas mini-CHPs. However, when considering the processes of operation and fuel combustion, the biogas mini-CHPs have greater advantages, and the diesel mini-CHPs have the worst indicators.

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Table 3. Results of the LCA mini-CHP calculation.

Impact direction	PI type					
	Biogas		Gas piston		Diesel	
	PI	Fuel	PI	Fuel	PI	Fuel
Mass of natural resources, t	95		41	377	37	250
Station area, m ²	20600		12.5		30	
Waste mass, t	82		37		33	11
Given the mass of waste, t	2314		577		521	1754
Water consumption, m ³	1881		592	146	541	895
Volume of wastewater, m ³	394		123	21	112	111
Conditional mass of harmful substances in wastewater, kg	585		241	58	169	9678
The reduced mass of harmful substances emitted into the air, t	6.8	451	4.9	218	4.5	462
Greenhouse gas emissions, t CO ₂ equivalent	27	551	10	635	9.2	754
Thermal pollution, GJ / year	5150		7250		6400	
Electricity consumption thousand, kW * hour	35		17	29	15	43

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