EXPRESS ENVIRONMENTAL EVALUATION OF THE IMPACT OF BIOGAS PROJECTS ON ATMOSPHERIC AIR

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ABSTRACT
Greening the global energy sector implies the development and implementation of large-scale energy projects around the world. The quality and effectiveness of the environmental assessment plays a central role in achieving the declared results of eco-modernization: the ability to comprehensively and quickly assess the current activities of an energy facility or an investment project planned for implementation allows one to quickly implement environmental and management solutions. The energy sector is the largest emitter of greenhouse gases into the atmosphere and the largest consumer of natural resources; this is what one considers in most of the proposed approaches to environmental assessment in the scientific and methodological literature. However, in addition to greenhouse gas emissions (in particular CO_2), energy facilities operating on traditional and alternative fuels consume a significant amount of oxygen as a result of their combustion, which also has a number of negative environmental consequences. The purpose of the study is the development of a methodology for rapid environmental assessment of energy projects, taking into account CO_2 emissions and oxygen consumption. The article presents specific indicators of oxygen consumption and CO_2 emissions per unit of generating capacity for various types of fossil and alternative fuels and their adoption on the example of a biogas project at a regional energy facility.
Keywords: express environmental assessment, biogas projects, energy sector.

1 INTRODUCTION

More than 60% of the world's electricity in 2022 was obtained from minerals: 35.72% from coal, 22.12% from natural gas and 3.1% from refined petroleum products [1]. The combustion of coal and oil in the process of heat and electricity production leads to the release of a huge amount of toxic substances. Besides, all fossil fuels, including natural gas, contribute to the emission of greenhouse gases (GHG) into the atmosphere that cause irreversible climatic changes and changes in local ecosystems [2], [3].

Greening the energy sector is a priority task of the world economy for the upcoming decades as part of the transition to a low-carbon development model. The directions of greening the global energy sector include the development of renewable and hybrid energy, the abandonment of the use of coal and fuel oil, eco-modernization of existing traditional energy facilities and the development and improvement of energy storage technologies [4]–[7]. All this requires the involvement of a large amount of financial, labour and intellectual resources and implies the implementation of large-scale investment projects [8].

Some of the measures applied have already demonstrated their effectiveness; in particular, the decommissioning of coal-fired power plants in OECD countries has significantly reduced the amount of toxic emissions into the atmosphere (Fig. 1).

However, despite the measures taken, energy is still an industry that has one of the greatest negative impacts on the environment: in 2021, electricity and heat production accounted for 39.4% of all CO_2 emissions, in 2022 – 39.8% [10]. The structure of global energy consumption in the period from 2012 to 2021 also showed no revolutionary changes (Fig. 2).

The share of oil in total energy consumption is more than 30%, coal's about 27%, natural gas's 24.4%. At the same time, there is a decrease in the share of coal from 29.8% in 2012 to

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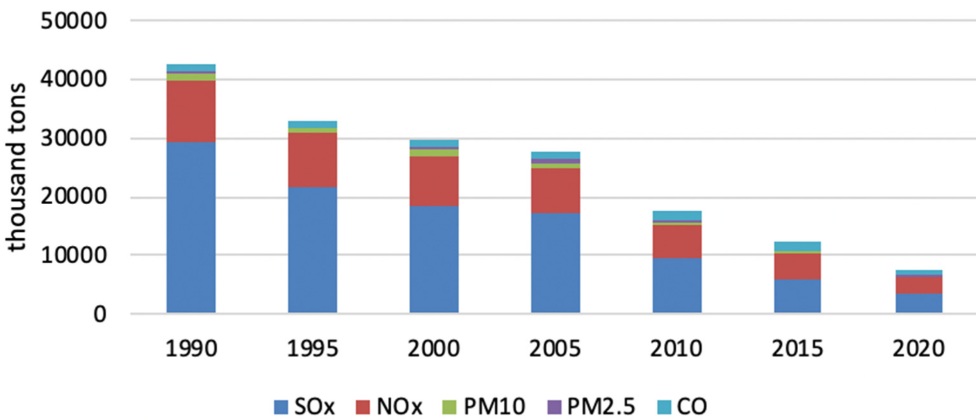

Figure 1: Toxic substances emissions by OECD countries from 1990 to 2020, thousand tons. *(Source: Compiled by the authors using data from [9].)*

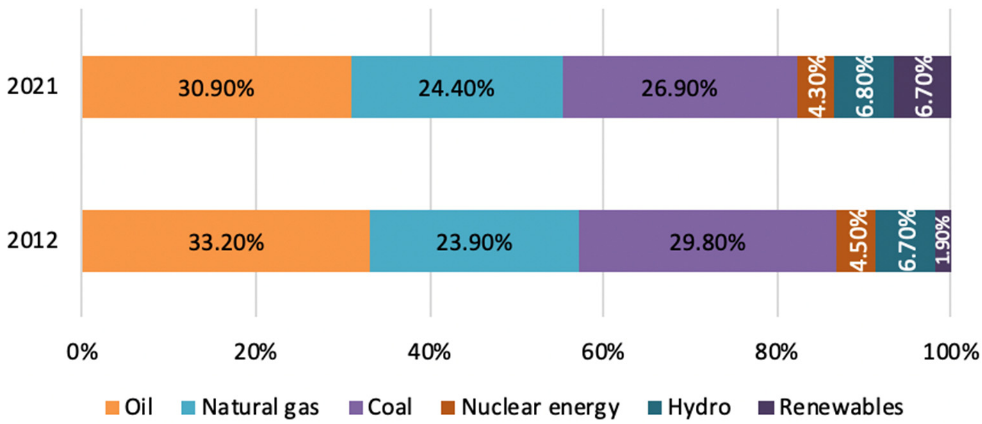

Figure 2: Structure of energy consumption by energy source in 2012 and 2021. *(Source: Compiled by the authors using data from [11], [12].)*

26.9% in 2021; a similar trend is observed with respect to oil consumption. The contribution of nuclear energy, hydropower and renewable energy increased by 4.7% from 13.1% in 2012 to 17.8% in 2021, which can be assessed as a positive trend. The change in the structure of global energy consumption is associated with scientific and technological progress and, in general, with economic development, however, with an increase in the number of energy sources, none of them has lost its significance to date.

In order to successfully implement the task of greening the energy sector, it is necessary to improve approaches to the environmental assessment of traditional energy facilities, which currently prevail in the structure of world energy [13], [14]. It should be noted that some types of alternative energy, in particular bioenergy, also require the use of adaptive approaches to assessment: the combustion of alternative fuels also produces emissions of GHG and toxic substances into the atmosphere [15]–[17]. In the scientific literature, most of the works on improving approaches to environmental assessment in the energy sector focus on the assessment of CO_2 emissions and toxic substances into the atmosphere [18]–[20]. Some authors include an assessment of the impact on the ozone layer [21], [22], on water resources [23], land resources [24] and an assessment of global warming potential [21], [25].

However, traditional and bioenergy enterprises have an impact on the atmosphere not only by emitting GHG and toxic substances, but also by consuming oxygen in the process of burning organic fuel. Up to 140 billion tons of free oxygen enter the atmosphere annually as a result of photosynthesis, while a decrease in oxygen concentration in the atmosphere has been recorded since 1989 [26], [27]. With an increase in the extraction and burning of organic fuel, industrial oxygen consumption together with natural consumption may exceed the level of its natural reproduction, which may have irreversible consequences for humans and the ecology of the planet [28], [29]. A review of the literature has shown that currently there are practically no works that consider the assessment of oxygen consumption by an energy facility as part of an environmental efficiency assessment.

It was earlier proposed to take into account both emissions of toxic substances and carbon dioxide and oxygen consumption when calculating the total environmental damage to atmospheric air caused by the operation of vehicles when considering the negative consequences of burning gasoline and diesel fuel in internal combustion engines [30], [31]. Considering the significant consumption of atmospheric oxygen and emissions of carbon dioxide in the processes of fuel combustion in stationary energy facilities, it is advisable to take these factors into account when assessing the environmental consequences for energy projects and enterprises.

The purpose of this study is the development of a methodology for rapid environmental assessment of the implementation of energy projects, taking into account CO_2 emissions and oxygen consumption. The article presents specific indicators of oxygen consumption and carbon dioxide emissions per unit of generating capacity for various types of fossil fuels and their adoption on the example of a biogas project at a regional energy facility.

2 MATERIALS AND METHODS

The methodology for express assessment of the potential environmental impact during the implementation of biogas projects includes the determination of the specific indicators of oxygen consumption and carbon dioxide emissions per unit of generating capacity for various fossil fuel types. It is assumed that the estimation of these indicators will be carried out per fuel weight value. However, indicators for all fuel types, excluding natural gas, will be calculated in reference to natural gas weight to simplify the use of the methodological tool.

2.1 Calculating specific indicators

Due to the different calorific values of different types of fossil fuels, different amounts of fuel are required to generate the same power. For natural gas, the mass content of carbon and hydrogen in the fuel will be assumed as is C = 75% and H = 25% respectively, neglecting natural gas components except methane. In this case, the stoichiometric combustion eqn (1) will be as follows [32]:

$$CH_4 + 2O_2 = CO_2 + 2H_2O. \tag{1}$$

Oxygen consumption $G_{O_2}^{NG}$ (tons) during the combustion of natural gas (NG) can be estimated using eqn (2):

$$G_{O_2}^{NG} = 4G_{CH_4}, \tag{2}$$

where G_{CH_4} is the weight of methane, in tons.

For mazut (M) and coal (C) in general, oxygen consumption $G_{O_2}^{f}$ (tons) during the stoichiometric combustion of liquid and solid organic fuel can be approximately estimated using eqn (3):

$$G_{O_2}^{f} = (0.027 \cdot C + 0.08 \cdot H + 0.01 \cdot S - 0.01 \cdot O) \cdot G_f, \tag{3}$$

where G_f is the weight of fuel, in tons; C, H, S, O are, respectively, percentages of carbon, hydrogen, sulphur and oxygen in the fuel composition.

Carbon dioxide emissions (tons) can be calculated using eqn (4):

$$G_{CO_2} = 3.67 \cdot G_f \cdot \frac{C_f}{100}, \tag{4}$$

where G_f is the weight of fuel, in tons; C_f, the percentage of carbon in fuel, 3.67%, is the coefficient of carbon content in the fuel conversion into carbon dioxide emissions during its combustion.

To compare the weights of different fuels reduced to equal generated power and GHG emissions during their combustion, the data on the elemental composition of fuels in Russia were used. The values are presented in Table 1.

Table 1: Elemental composition of fuels in Russia. *(Source: Compiled by the authors using data from: [33], [34].)*

Fuel type	Elemental composition, %				Source
	C	H	S	O	
Mazut (M)	85.8	10.4	3.0	0.8	[31]
Coal (C)	80.0	4.0	3.0	13.0	[32]
Brown coal (BC)	65.0	4.0	3.0	28.0	[32]

The following set of indicators was used to build a project efficiency matrix for environmental impact assessment.

The caloric equivalent of fuel type ($Э_f$), reduced to a similar indicator for natural gas, is calculated using eqn (5):

$$Э_f = \frac{LHV_f}{LHV_{NG}}, \tag{5}$$

where LHV_f is the lower heating value of fuel type, Mj/kg; HV_{NG} the lower heating value of natural gas, Mj/kg.

The ratio of the weight of different fuel type, compared to the weight of natural gas, is calculated using eqn (6):

$$k_{NGeq}^{f} = \frac{G_f}{G_{NG}}, \tag{6}$$

where G_f is the weight of fuel type, in tons; G_{NG} the weight of natural gas, in tons.

The oxygen consumption during fuel combustion, reduced to natural gas equivalent, is calculated using eqn (7):

$$k_{NGeq}^{O_2} = \frac{G_{O_2}^{f} \cdot G_f}{G_{NG}}, \tag{7}$$

where $G_{O_2}^{f}$ is the weight of oxygen for fuel type, in tons.

The carbon dioxide emission during fuel combustion, reduced to natural gas equivalent, is calculated using eqn (8):

$$k_{NGeq}^{CO_2} = \frac{G_{CO_2} \cdot G_f}{G_{NG}}, \tag{8}$$

where G_{CO_2} is the weight of carbon dioxide, in tons.

2.2 Project efficiency matrix

The calculated values of indicators for the project efficiency matrix for the equal generated power of the power plant are presented in Table 2. Lower heating values were used according to Khartchenko and Kharchenko [35]; in particular, the natural gas (NG) and biogas (BG) values were calculated using the density of 0.8 kg/m^3 and 1.4 kg/m^3, respectively [36] with the methane content in BG of 50%.

According to Table 2, the specific oxygen consumption during the combustion of natural gas, mazut and coal to generate the equal energy have similar values.

It should be noted that for the combustion of biogas, adjusted for the caloric equivalent of the fuel type, more oxygen is required for combustion of the fuel. However, this factor does not have a noticeable negative impact on the atmospheric air, since biogas is mainly applied in distributed generation and micro-energy networks to partially replace the traditional generation, in the organic raw material production areas (wastewater treatment plants, livestock farming, municipal organic waste dumps, etc.).

At the same time, for brown coals, oxygen consumption is much higher, which can be a significant factor influencing air quality and public health when this type of fuel is used at small provincial thermal power plants, in provincial boiler houses with insufficient green areas. A decision making procedure on energy reform should take into account the peculiarities of the brown coal applications within the considered territories.

For other types of fuel, oxygen consumption is not a significant factor in the environmental efficiency of projects. The significant difference in emissions of toxic substances and GHG has a much greater impact; from this point of view, the most desirable type of fuel is natural gas and biogas.

2.3 Case study area and materials

The proposed methodological framework was tested on the project implementation at wastewater treatment plant (WWTP) in Ekaterinburg, Russian Federation.

In 2018, two digesters with the total volume of 10,000 m^3 were put into operation at the northern WWTP with a potential generation of electrical energy via combined heat and power (CHP) unit of 4,642,800 kWh per year, while total energy consumption from the grid before project implementation was of 6,610,680 kWh per year [37].

The two large generating facilities generate more than 50% of all Sverdlovsk region energy production; these are the Reftinskaya GRES and the Sredneuralskaya GRES [38]. The coal-fired generation is applied at the former one, while the combustion of the natural gas is used at the latter one.

Taking into account the integrated nature of the energy system in the Sverdlovsk region, the authors identified the following options with certain assumptions: option ‘A’ implies the energy supply of WWTP from the grid only taking into account the generation of the

Table 2: Values of indicators for the project efficiency matrix for the equal generated power of the power plant.

Indicator	Fuel type				
	Natural gas	**Biogas**	**Mazut**	**Coal**	**Brown coal**
LHV_f, Mj/kg	43.8	12.8	40	30	10
$Э_f$	1	0.29	0.91	0.68	0.23
k_{NGeq}^{f}	1	3.4	1.1	1.5	4.4
Oxygen consumption equation for fuel type, tons/tons of fuel	$G_{O_2}^{NG} = 4G_{NG}$	$G_{O_2}^{BG} = 2G_{BG}$*	$G_{O_2}^{M} = 3.17 \cdot G_M$	$G_{O_2}^{C} = 2.21 \cdot G_C$	$G_{O_2}^{BC} = 1.83 \cdot G_{BC}$
$k_{NGeq}^{O_2}$, tons/tons of fuel	4	6.8	3.5	3.32	8.05
Carbon dioxide emission equation for fuel type, tons/tons of fuel	$G_{CO_2}^{NG} = 2.75G_{NG}$	$G_{CO_2}^{BG} = 0$**	$G_{CO_2}^{M} = 3.15 \cdot G_M$	$G_{CO_2}^{C} = 2.94 \cdot G_C$	$G_{CO_2}^{BC} = 2.39 \cdot G_{BC}$
$k_{NGeq}^{CO_2}$, tons/tons of fuel	2.75	0	3.5	4.4	10.5

* With methane content in BG of 50%.

** CO_2 emissions from biogas combustion are considered zero, taking into account its carbon neutrality.

Reftinskaya GRES, and option ‘B’, in turn, only the generation of Sredneuralskaya GRES. The selected options will clearly demonstrate the application of the methodology, since they take into account different types of fuel for traditional energy generation.

3 RESULTS AND DISCUSSION

Using the project efficiency matrix, the initial case study data were applied to calculate the resulting indicator values in two sections: before and after the project implementation. The resulting values before project implementation are presented in Table 3.

Table 3: Resulting values before project implementation.

Fuel type (options)	G_f, tons	$G^f_{O_2}$, tons	$G^f_{CO_2}$, tons	P, kWh
Option ‘A’: Reftinskaya GRES generation	793.28	1,803.90	2,390.71	6,610,680
Option ‘B’: Sredneuralskaya GRES generation	543.34	2,173.37	1,494.19	6,610,680

To calculate the resulting values after the project implementation, it should be considered that energy generation by burning biogas does not fully cover the energy demands of WWTP. It is necessary to take into account simultaneous generation from various sources (option ‘A’ + biogas; option ‘B’ + biogas). The resulting values after project implementation are presented in Table 4.

Table 4: Resulting values after project implementation.

Fuel type (options)	G_f, tons	$G^f_{O_2}$, tons	$G^f_{CO_2}$, tons	P, kWh
Biogas generation	1,305.79	2,594.88	0.00	4,642,800
Option ‘A’: Reftinskaya GRES generation	236.15	536.99	711.67	1,967,880
Option ‘B’: Sredneuralskaya GRES generation	161.74	646.97	444.79	1,967,880

A comparative diagram of the environmental effect from the implementation of a biogas project at the Northern WWTP of Ekaterinburg (Russian Federation) using the project efficiency matrix is presented in Fig. 3.

Commenting on the diagram outputs (Fig. 3), through the implementation of the biogas project, the volume of carbon dioxide emissions is significantly reduced, and this effect is much stronger within coal-fired generation compared to natural gas applications. Regarding oxygen, its consumption rate increases by 1.5 to 1.7 times throughout biogas combustion. However, given the distributed nature of CHP units and the small power of each (compared to traditional generation), this situation does not lead to negative environmental consequences.

4 CONCLUSIONS

The methodological approach to quick environmental air impact estimation of the investment projects to replace traditional generation based on fossil fuel burning with renewable energy sources running on biogas was considered and discussed within the manuscript.

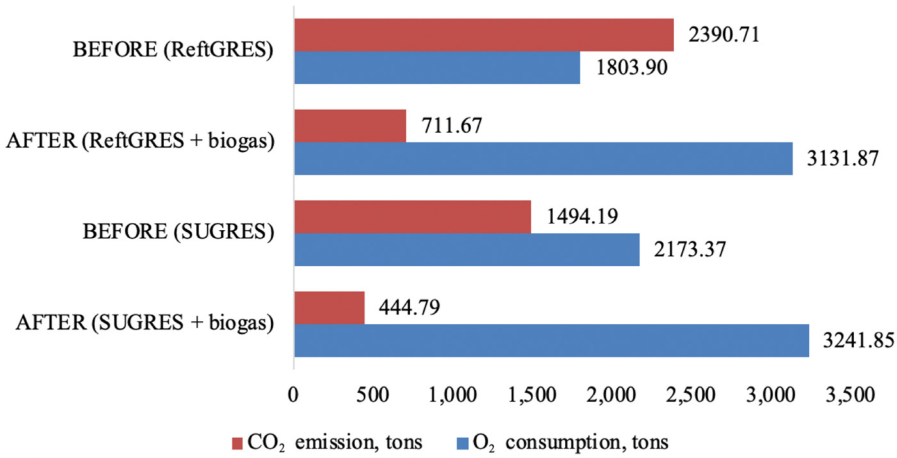

Figure 3: Environmental effect from the implementation of a biogas project.

As the main tool, the project efficiency matrix is proposed, where the values of key performance indicators regarding the impact on atmospheric air are reduced to the generation of the electrical power unit and expressed in natural gas equivalent.

The solutions proposed in the article were tested at a real-life generation facility based on the biogas energy use; the results of the investigation confirmed the application simplicity and representativeness of the method. The described approaches can be applied throughout the decision-making procedure of various groups of stakeholders, including strategic documents formation on the development of energy sector and environmental safety and alternative options comparison via modernization activities.

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