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# CONSTRUCTION OF MATHEMATICAL MODEL THE COMBUSTION OF BIOGAS TO REDUCE GREENHOUSE GAS EMISSIONS

**Abstract.** This paper shows the environmental and economic efficiency of biogas. An analysis of the prospects for world energy development shows a marked shift of priority issues in a comprehensive assessment of the possible side effects of the impact of major sectors of energy on the environment, the life and health of the population. Energy conservation measures and environmental security are aimed at increasing the use of CHP and renewable energy sources. The main advantages of CHP are: low cost of energy, low return on investment, the ability to quickly build, and reducing environmental pollution. The main advantage of renewable energy sources is the use of the inexhaustible source of energy, such as solar, wind and biofuels. The paper discusses the various sources of energy capacity of 1 MW mini-thermal power station with diesel, gas piston and turbine engines, as well as renewable energy-generation plant with a gas-piston engines running on biogas, solar and wind power. It was found that all sources participate in the emission of greenhouse gases. Gas turbine engines emit more greenhouse gases than other motors. The most environmentally friendly way to produce electricity is solar panels. This paper shows the environmental and economic efficiency of biogas in the brewery. The article used the standard method for determination of greenhouse gas emissions through the levels. Calculations for natural gas and biogas were made. The results of the calculations showed that the amount of greenhouse gas emissions from the combustion of natural gas and biogas in the boilers reduced. The efficiency of co-combustion of these fuels was determined. It is shown that co-combustion of natural gas and biogas will reduce the emission of gases by 10%.
**Keywords:** bioreactor, biogas, bacteria, adjusting, mathematical model, distributed system, optimal control, integration, aggregation, computer simulation.

**Introduction.** Improvement of the efficiency of heat sources is one of the main priorities in the development of new and modernization of existing heat-generating devices. The deteriorating ecology, as well as the global crisis leads to a search for new methods of heat supply management that would ensure ecological and economical heating. In order to develop new, environmentally friendly technologies for the production and processing of biomass we must develop a basis of these processes. Although biogas as an energy source is known for many centuries, it remains a matter of concern of engineers and scientists in both experimental [1-3] and theoretical studies. Therefore, the development of mathematical models and biogas combustion process is an interesting task carried out by researchers. Numerical simulation is an intersting, inexpensive and rapid method for analyzing problems and leads to understanding of the mechanisms in this process. But the numerical simulation should be preceded by the creation of a mathematical model which describes the phenomena. Depending on the complexity of these problems, the mathematical model can describe the monitoring process with various degrees of certainty. Thus, numerical simulation should be combined with experimental studies in order to compare and assess the validity of the model. The mathematical model of biogas combustion will be presented below. Then, on the basis of the results of experimental studies in order to validate the developed mathematical model there will be conducted numerical simulation of biogas combustion. The process of biogas burning is complex heterogeneous and homogeneous combustion. Combustible gases – mainly CO, $H_2$, $CH_4$ – together with other non-combustible gases such as $CO_2$, $H_20$, N, particles are emitted during degasification – are subject to homogeneous combustion. Combustible components of solid material, mainly carbon in particle, so called carbonated coal, after degasification are suspectible to the heterogeneous combustion. Due to the complexity of the processes in homogeneous-heterogeneous combustion, it is assumed that the mathematical model of biogas combustion process will describe the process in a simplified form, in other words, using Euler-Lagrange method, which is the standard method used for numerical simulation of combustion of biogas and particles or droplets of combustible material [2-5]. The model assumes that the biomass particles will be considered as a discrete Lagrangian particle that creates the boundary conditions for the gaseous medium, viewed as Euler Wednesday. On the basis of analogy with the gaseous medium, the evolution of the particle is described by the equations of conservation of mass, momentum and energy. Thus, the aim of this work is the adaptation of a mathematical model of the combustion process, based on the theory of I. Wiebe to the process of combustion of biogas.

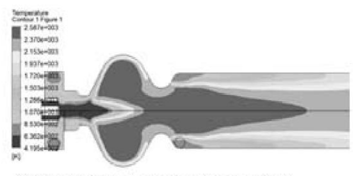
**Research methods.** Monitoring and control of the efficiency and emissions in industrial combustion of biogas is one of the greatest challenges faced by the society due to the use of fossil fuels and climate change.

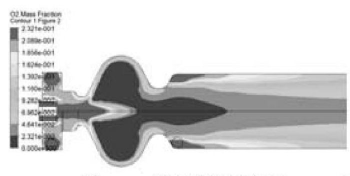
There are different methods of adjusting the combustion of biogas:

- Preliminary determination of the heat capacity of the chemical composition of biogas and air-fuel ratio;
- Monitoring of biogas combustion in situ using optical sensors and timely control of air-fuel ratio;
- Measuring the concentration of gases such as oxygen, carbon monoxide or carbon dioxide in the exhaust and adjusting.

The measurement of oxygen concentration is most suitable for testing the efficiency of biogas combustion process because oxygen and excess air are almost independent of the fuel type. The method of adjusting the biogas combustion by measuring the concentration of gases in the exhaust is appropriate due to the development of modern sensors. Initially, different types of sensors have been developed for the control of biogas combustion efficiency and these technologies recently have been adapted for industrial furnaces, boilers and gas turbines. Organization of biogas combustion process is associated with permanent control. This is because the combustion of fuels with a large excess of air leads to unnecessary losses of heat consumed for warming the excess air and its emission into the atmosphere. Fuel combustion with air deficiency also causes high losses of energy due to chemical unburnt fuel, as evidenced by the CO in the flue gas. Optimal combustion conditions are achieved by some content of unused oxygen and CO in the flue gases. For one and the same furnace, depending on load, the minimum may be different. According to the research and calculations, 5-25% of CO and 3.2% of oxygen in the flue gases content is optimal. The CO content characterizes the quality of fuel combustion and the content of $O_2$ – the efficiency of furnace.

Automatic devices that support constant ratio of incoming air and fuel play major role in maintaining the optimal mode in the furnace. At biogas burning, the control of the combustion process and the maintenance of a regime is largely facilitated by using burners that have important property of automatically adjusting, maintaining a constant composition of the gas air mixture at changing the burner load (Figure 1).





А) Распределение температуры в сечении горелки с двумя подводами воздуха при $\alpha = 1,3$

Б) Распределение массовых концентраций кислорода в сечении горелки с двумя подводами воздуха при $\alpha = 1,3$

В) Поле скоростей в сечении горелки при $\alpha = 1,3$

Figure 1 – Temperature distribution in the cross section of the burner

The energy obtained in the process of biogas combustion can be used to heat water, heat generation for technological needs and heating, to provide autonomous power. Processed biomass can be used as an environmentally friendly fertilizer (Figure 2, 3).


Figure 2 – System of receiving and combustion of biogas

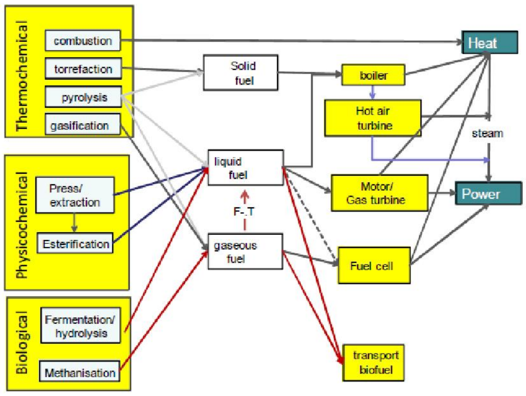



Figure 3 – Different ways to transform the energy of the biogas

This complicated problem can be solved by methods of mathematical simulation. The followings equations are sugessted as the initial equations of the study:

$$
\left.
\begin{aligned}
&U_2 = r_2 i_2 + \frac{d\psi_2}{dt} \\
&M_2 = \operatorname{Re} j(\psi_2 i_2) + J\frac{d\Omega}{dt} \\
&U_f(t) = k_u U_2 + k_i i_2 \\
&n = f[\omega(t)] \\
&M_m = f[\omega(t), ЭВ] \\
&Z_э = \frac{Z_н(2^N - 1)}{2^N + Z_н(n-1)/n = 0 \div (2^N - 1)} \\
&U_2 = (R_э + jX_э) i_2 + x_2 \frac{di_2}{dt}
\end{aligned}
\right\}
$$

The proposed mathematical model of the combustion process involves the following assumptions:

– Fuel air mixture is divided into infinitely thin flame front in the zone of the burnt mixture and in the zone of the unburned mixture;

– The working medium in both zones is an ideal gas;

– The chemical composition of the working medium is different in the zones, so its thermal and physical characteristics are different;

– The pressure in both zones is the same;

– There are no gradients of working meduim parameters on the coordinates within each zone, but the temperature is different between the zones;

– Heat output characteristics are calculated using dependence of I. I. Wiebe;

– Indicator and efficient engine performance are determined by the method of I. I. Wiebe taking into account variables of combustion nature and duration of combustion of the fuel;

– The toxicity indicators are calculated using the methodology V. A. Zvonov [5, 6].

One of the most popular methods which most accurately describe the characteristics of heat output of mathematical models is the model of the combustion process I.I. Wiebe, which is most prevalent.

The averaging of temperature in the engine cylinder, which reduces the accuracy of the calculation of toxicity indicators, is the basic assumption which is the basis of mathematical model of the combustion process of I. I. Wiebe. The increase of the accuracy and efficiency of the use of this mathematical tool is possible through the introduction of two-band model of calculation of the combustion process, which allows us to accurately assess the indicators of exhaust emission [23, 24].

We use two-band model of the combustion process which uses I.I. Wiebe model to define the characteristics of heat output and combustion duration. Adaptation of models data is also performed in order to investigate the combustion process in the biogas engine with spark ignition on diesel using engine.

Design scheme of used two-zone mathematical model of the combustion process is presented in Figure 4.

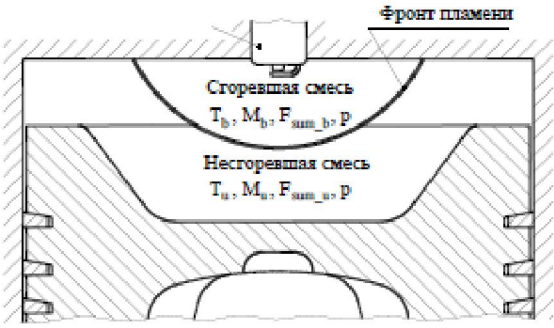



Figure 4 – Driving two-zone mathematical model of the combustion process

The researches of biogas technology aimed at obtaining a high-speed processing technology of biomass into biogas have been conducting in the past four years. Unexpectedly produced results were highly appreciated by Polish experts from the scientific community. Despite the seeming simplicity of installation in the Polish laboratory LPU (Lublin, Poland), which were hand made, they were made hundreds of experiments on the study of biogas processes. Factual data on gas concentration, controlling, logging had been received using advanced equipment, for example, with the use of gas analysis.

**Results of the research.** In order to study the produced biogas as a fuel for the production of electrical energy, the laboratory stand purchased by our partner university – the Institute of Electronics and Information Technology, Lublin Technical University, Poland was used (Figure 5).

Figure 5 – The appearance of the installation for the combustion of biogas

The system is designed to the effect that a high efficiency coefficient is achieved. Combination of power, heat and cold ensures a high yield of electrical energy while the residual heat is used for the entire technological process. The thermal energy of the engine exhaust gas is used to produce superheated water, and the waste heat of the engine is used to produce hot water. The energy of the exhaust gases from the venting channel of gas removal is selected through the heat exchanger and is used for air pre-heating which is involved in the combustion process. Besides, waste heat can be used by other users depending on the installation location. Obtaining of adjusted equations of mvar biogas combustion variables and $\varphi_z$ combustion duration was based on the results of preliminary experimental studies. The studies were conducted in the whole range of speed and load modes of object operation and different combinations of biogas. Verification of the developed mathematical model of biogas combustion is carried out by comparison of calculated and experimental characteristics of heat output and graphs of combustion character variables depending on the relative duration of the combustion process. Control of the mathematical model was carried out on twenty modes of object according to the speed and load characteristics in the range of changes of affecting parameters. Although the indicators of cycle performance and effective indicators of control object were estimated. The mathematical precision of the model allows using obtained data to assess the sensitivity of the results taking into account errors of measuring channels: temperature of combustion products and costs of fuel and oxidant (Figure 6).

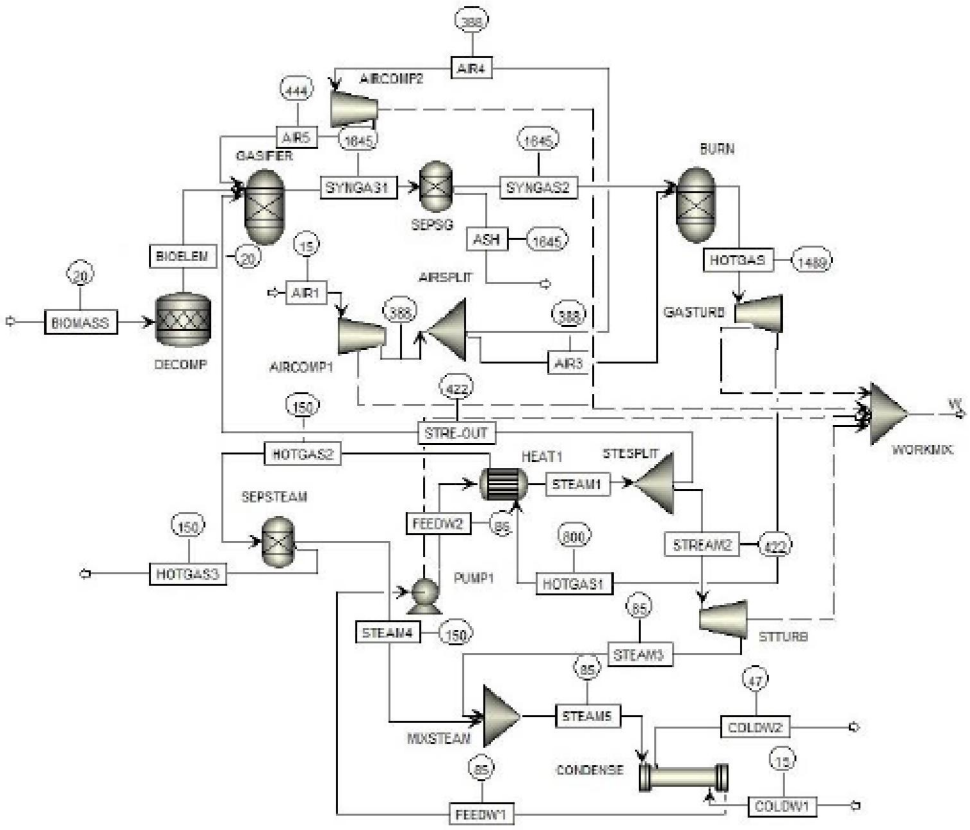



Figure 6 – Simulation of the scheme of control in a program Aspen Plus

The simulation results of the automatic control system of unit operation confirmed the efficiency of the developed model. The resulting model of extreme adjusting of the combustion process in the furnace enables to improve the energy performance of the work by maintaining optimal efficiency values (Figure 7). The efficiency of the developed simulation model of extreme adjusting at changing the reference signal, in other words, the maintenance of the boiler efficiency at the same level with a given accuracy has been proved. Modern technology for municipal sewage treatment is connected with the consumption of significant amounts of electric and heat energy. Under the conditions of huge energy crisis, the problem of reducing the energy costs through the use of alternative energy sources is topical.

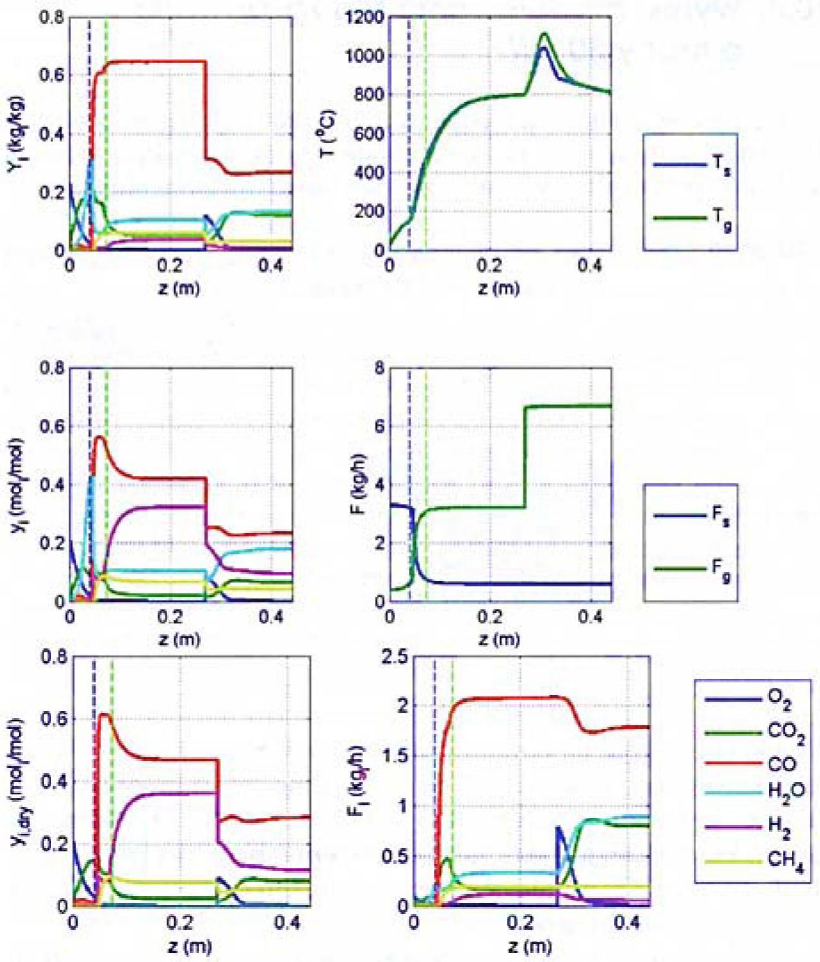



Figure 7 – The calculated curves showing steady state process of gasification.

a – temperature profiles, b – gas composition (% by volume), c – degree of fuel conversion, d – heat sources (in % of the calorific value of the fuel). Abscissa-distance from tuyeres.

This article considered an installation for co-incineration of biogas and natural gas as an object of control. Mathematical model and method that allows determining its composition and providing optimal parameters of the combustion process was proposed. The mathematical models of the process of adsorption of biogas and natural gas were developed.

**The discussion of the results.** Heat losses during the fermentation limit the degree of efficiency of the whole process, which efficiency factor is 50-60%. Two heat settings in which the fermentation process is usually carried out such as mesophilic and thermophilic found the most practical application. Less energy intensive mode of mesophilic, thermophilic is mainly used abroad, though looks better in terms of speed of the process and the hygienic properties of the fermented residue – effluent (absence of contaminating and toxic substances), which can be used for phosphorus and nitrogen biofertilizers. Nowadays, it has now been developed and increasingly used specially designed bioreactors for recycling of waste process solutions and wastewater by methanogenic bacteria (so-called "bioreactors for anaerobic biological treatment of waste water").

This paper proposed a new type of high-performance environmentally friendly energy installations of small capacity, using a combination of renewable energy sources like biogas and natural gas as a fuel. This approach is based on an efficient method for biogas combustion using "fast reactor" technology and the new technology of environmentally friendly combustion of low-calorie fuels in bulk matrix burner.

The oxidation in suspension occurs in a combustion wave in the high temperature reactor at pressures up to 100 atm and temperatures of 2500 - 3000 ° C with separate generation of hydrogen and power steam.

In the first stage, combustion of stoichiometric suspension with formation of hydrogen is carried out. In the second stage after selecting the hydrogen, an additional quantity of water, which turns into the high-potential steam at interaction with gas, is given to the reactor. After removing of gas oxide, the process can be repeated. This avoids the contact of fine particles in the power plant. As a device for burning a low-calorie biofuel, there used a bulk matrix burner. The ability of stable combustion in a low-calorie biogas in such hybrid energy installation is provided by features of the combustion unit on the basis of bulk matrix and application of the hydrogen generated during the combustion of the suspension. Thus, this combined energy installation allows combining the combustion processes of two different types of renewable energy sources in a single energy process, which enables the hydrogen to maintain sustained combustion in the matrix burner device of low-calorie biogas, thereby ensuring environmentally friendly production of energy from renewable energy sources for distributed power.

**Conclusions.** Modern technology is connected with the consumption of significant amounts of electric and heat energy. Under the conditions of huge energy crisis, the problem of reducing the energy costs through the use of alternative energy sources is topical. This article considered an installation for co-incineration of biogas and natural gas as an object of control. Mathematical model and method that allows determining the composition of fuel during combustion and providing optimal parameters of the combustion process was proposed. The mathematical models of the process of adsorption of biogas and natural gas were developed.

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## ПАРНИКТІК ГАЗДАР ШЫҒАРЫНДЫЛАРЫН АЗАЙТУ БИОГАЗДЫ ЖАҒУ ҮШІН МАТЕМАТИКАЛЫҚ МОДЕЛІ

**Аннотация.** Қағаз биогаз экологиялық және экономикалық тиімділігін көрсетеді. Әлемдік энергетиканы дамыту перспективалары талдау басымдық бағытта айтарлықтай ауысым халықтың қоршаған ортаға ірі энергетикалық саласының әсер, өмірі мен денсаулығына ықтимал салдарын жан-жақты бағалауды шығарады көрсетеді. Энергия үнемдеу және экологиялық қауіпсіздік қызметі жылу электр станциялары және жаңартылатын энергия көздерін пайдалануды арттыру үшін бағытталған. Жылу электр станциялары негізгі артықшылықтары: өндірілген энергия құны төмен, төмен қайтару, тез салу мүмкіндігі, қоршаған ортаны ластау деңгейін төмендету. Жаңартылатын энергия көздерін басты артықшылығы, мысалы, күн, жел және биоотын ретінде энергия көзі сарқылмас пайдалану болып табылады. Қағаз 1 МВт жылу электр станциялары дизель, газ поршенді және турбиналық қозғалтқыштар мен биогаз жұмыс істейтін газ қозғалтқышы, күн және жел электр қуатымен жаңартылатын энергия жылу электр станциялары энергетикалық қуаты әртүрлі көздерін талқылайды. Ол барлық көздері Парниктік газдардың шығарындыларын тартылған деп табылды. Парниктік газ турбиналық қозғағыштар басқа қозғалтқыштар астам шығаратын. Электр энергиясын өндіру үшін ең экологиялық таза жолы күн батареялары бар. Қағаз зауытында биогаз пайдалану экологиялық және экономикалық тиімділігін көрсетеді. Мақала деңгейдегі арқылы парниктік газдар шығарындыларының анықтау үшін стандартты әдісі пайдаланылады. Табиғи газ және биогаз бойынша есептеу. Нәтижелері табиғи газды жағу және биогаз өндіру бастап парниктік газдар шығарындыларының көлемі қазандық төмендеді, деп көрсетті. Осы отынның тең жану тиімділігі. Ол табиғи газ және биогаз тең жану 10%-ға газдар шығарындыларының шығарылуын азайтуға болады деп көрсетілген.

**Түйін сөздер:** биореактор, биогаз, бактериялар, реттеу, компьютерлік модельдеу, таратылған жүйесі, оңтайлы басқару, интеграция, біріктіру.

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## ПОСТРОЕНИЕ МАТЕМАТИЧЕСКОЙ МОДЕЛИ ПРОЦЕССА СЖИГАНИЯ БИОГАЗА ДЛЯ СНИЖЕНИЯ ВЫБРОСА ПАРНИКОВЫХ ГАЗОВ

**Аннотация.** В работе показана экологическая и экономическая эффективность использования биогаза. Анализ перспектив развития мировой энергетики свидетельствует о заметном смещении приоритетных проблем в сторону всесторонней оценки возможных последствий влияния основных отраслей энергетики на окружающую среду, жизнь и здоровье населения. Мероприятия по энергосбережению и экологической безопасности направлены на увеличение использования мини-ТЭЦ и возобновляемых источников энергии. Основными достоинствами мини-ТЭЦ являются: низкая стоимость вырабатываемой энергии, низкая окупаемость, возможность быстрого строительства, снижение уровня загрязнения окружающей среды. Основным преимуществом возобновляемых источников энергии является использование неисчерпаемых источником энергии, таких как солнечная энергия, ветер и биотопливо. В работе рассмотрены различные источники энергии мощностью 1 МВт: мини-ТЭЦ с дизельными, газопоршневыми и газотурбинными двигателями, а также возобновляемые источники энергии мини-ТЭЦ с газопоршневыми двигателями, работающими на биогазе, солнечные и ветровые электростанции. Установлено, что все источники принимают участие в эмиссии парниковых газов. Газотурбинные двигатели выбрасывают парниковых газов больше, чем остальные двигатели. Самым экологичным способом производства электроэнергии являются солнечные батареи. В работе показана экологическая и экономическая эффективность использования биогаза на пивоваренном предприятии. В статье использована стандартная методика определения эмиссии парниковых газов по уровням. Выполнены расчеты для природного газа и биогаза. Полученные результаты показали, что количество выбросов парниковых газов от сжигания природного газа и биогаза на котлах уменьшаются. Доказана эффективность совместного сжигания данных видов топлива. Показано, что совместное сжигание природного газа и биогаза позволит снизить выбросы эмиссионных газов на 10%.

**Ключевые слова:** биореактор, биогаз, бактерии, регулирование, математическая модель, распределенная система, оптимальное управление, интеграция, агрегирование, компьютерное моделирование.

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