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AN ANALYSIS OF THE SYSTEMATISATION OF THE GLOBAL ENERGY AND ENVIRONMENTAL USE OF BIOMASS

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Abstract

The work is devoted to work out the technology of power usage of biogas, received as a result of anaerobic fermentation of biomass with the purpose of reducing fossils fuels consumption and greenhouse gases emission. The analysis of power biomass usage technologies in Ukraine has been made, the ways of solution of ecological problem greenhouse effect emergence and climate change connected with it have been formulated. The regularities of the influence of excess air on the environmental and thermal performance of the boiler were revealed, and the effects that occur when combusting mixtures of natural gas and biogas in different proportions were established. For the first time, the indicators of harmful emissions during the combustion of biogas in steel water heating boilers of low power, depending on the mode and design of the boilers, were determined.

Key words: the biogas, the heat generator, the greenhouse gases emission, the biomass, ecological efficiency, the economy of fuel, the harmful emission.

Introduction

The scientific novelty lies in the fact that for the first time a mathematical model of efficient use of biomass energy in the global energy sector has been developed and substantiated, which allows choosing a rational layout of power equipment, determining the optimal structure of consumed energy resources and the cost of generated energy.

The aim of the study is to create scientifically sound technologies, methods and means of improving the energy and environmental safety of hot water boilers that use bioenergy fuel for heat production, while developing scientific and methodological foundations for the environmental efficiency of energy use of biogas obtained from anaerobic digestion of biomass, based on the indicator of specific reduction of greenhouse gas emissions k_{CO_2}

Consumption of various types of energy is the basis for the existence and development of modern society. The continuous growth of production in modern society leads to an increase in energy consumption and, consequently, to an increase in the consumption of fuel and energy resources, which are further converted into heat and electricity.

Energy can be obtained both from non-renewable sources (coal, oil, natural gas, peat, nuclear energy) and from renewable sources (biomass, solar, wind, wave, geothermal energy).

The use of methods of biological conversion of organic waste to produce gaseous or liquid fuel is very promising at the moment. It allows solving not only the energy problem, but also the economic and environmental one, that is why it attracts attention of ecologists, power engineers, economists, and biotechnologists. It is very significant for agriculture, where there is a lot of organic waste. Perspective raw materials in bioenergetics are also wastes from food, microbiological, wood processing industry, waste water from public utilities.

The modern energy consumption is mainly reduced to the use of natural (primary) fuel and energy resources, such as fossil fuels and products of their processing (motor fuel, mazut) and nuclear fuel. This is mainly due to the relatively simple process of obtaining these fuels with their high energy potentials.

The most important factor affecting the energy and economic situation both in the world at large and for Ukraine in particular is the significant increase in energy prices, particularly natural gas. In this connection, the task of finding alternative sources of energy is becoming even more urgent.

As we know, the main energy consumers are industry, power and transport [1,2,3], and it is necessary to take into account that they consume a huge amount of primary resources in the form of solid, liquid, gaseous fuel and air oxygen, they return into the environment a significant amount of gaseous and solid pollutants.

One of the most important environmental issues at present is climate change. This has to do with the impact that this phenomenon is having on people's lives at present and in the foreseeable future. For example, in Ukraine alone, not to mention the world as a whole, the number of negative natural phenomena associated with climate change between 1997 and 1999 exceeded 20 [1]. The increase in average atmospheric temperature over the last 120 years has been 1÷1,2 °C [1,3], and a further warming of 3-5°C [2] is predicted in the XXI century. The main cause of this phenomenon, according to most experts, is the greenhouse effect caused by increased concentrations of greenhouse gases (CO_2, CH_4, N_2O, and others) in the earth's atmosphere.

In order to prevent and slow down the global warming process, the "Framework Convention on Climate Change" was developed in Rio de Janeiro in 1992, containing proposals for an inventory of greenhouse gas emissions and development of national plans to reduce them. In December 1997 in Kyoto (Japan) the Protocol of the Conference of the Parties of the Convention on Climate Change, which proposed specific mechanisms to reduce greenhouse gas emissions, was adopted. Ukraine ratified the Kyoto Protocol on 4 February 2004. It entered into force on February 16, 2005 [1,3-6].

Analysis of anthropogenic sources of greenhouse gases in Ukraine (fig. 1), [1,2] not to mention the world as a whole, shows that fossil fuel combustion for energy production constitutes a significant proportion of total emissions and determines the overall level of greenhouse gas emissions.

Thus, energy saving and replacement of fossil fuels with non-conventional and renewable energy sources (wind, solar and biomass energy) are the main emission control measures.

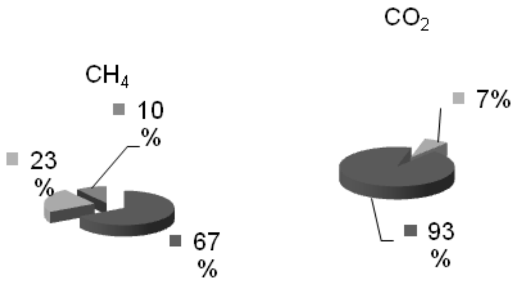

Fig. 1. Analysis of anthropogenic sources of greenhouse gases in Ukraine

Energy - 67 %
Agriculture - 23 %
Waste - 10 %

Natural fuel combustion - 93 %
Industrial processes - 7 %

The difference between biomass and other types of renewable energy when replacing fossil fuels is the following. The burning of biomass emits a corresponding amount of greenhouse gases, but as it grows, a similar amount of CO_2 is absorbed and thus there is no increase in the concentration of greenhouse gases in the atmosphere.

In addition, the use of wood as fuel reduces the emission of carbon oxides and sulphur into the atmosphere by up to 10% of the total amount of oxides generated by burning the widely consumed oil with high sulphur content in the world [1, 2].

Nevertheless, one of the main requirements for biomass energy technologies is to meet all environmental regulations and, first of all, to reduce as much as possible the emission of carcinogenic substances originating from biomass combustion [7-12].

The term biomass (BM) usually refers to carbon-containing organic substances of plant and animal origin (wood, straw, manure, etc.). Often the organic fraction of the organic fraction of municipal solid waste is also included in the term biomass.

Municipal solid waste. As a raw material for energy production biomass takes the first place among all kinds of renewable energy sources (RES) used nowadays [1,2,13,14], which is equivalent to 1250 mln. tce and makes about 15 % of primary energy sources in the world (in developing countries - to 38 %) [1,2]. It also plays significant role in industrialized countries - on the average 23 % of the total energy consumption (TEC): in the USA its share is 3,2 % [1,2], in Denmark - 6 % [2], in Canada - 7 % [1, 2], in Austria - 13 % [2], in Sweden - 16 % [1], in Finland - 20 % (maximum share for developed countries) [1, 2]; BM advantages as a fuel Complete absence or insignificant emission of sulphur compounds and preservation of equilibrium of carbon dioxide CO_2 in atmosphere. " The most widely used at present is vegetable BM.

The forecast of the World Energy Council (WEC) concerning the contribution of biomass in the energy sector of the future along with other renewable energy sources (RES) is shown in Figure 2 [17]. The term "modern biomass" means usage of modern industrial technologies of generation; energy production from biomass (domestic use of biomass for heat production and cooking is excluded). According to the prognosis the share of BM will make 42-46% of total share of RES in 2020, significantly exceeding contribution of solar, wind, geothermal and other types of RES.

Now in many countries there are plantations of fast-growing trees and high-yielding crops for energy needs (cultivation of rape for motor fuel in Germany, plantations of fast-growing wood species in Sweden, cultivation of sugar-cane for ethanol production in Brazil, etc.) [1, 2]. [1, 2].

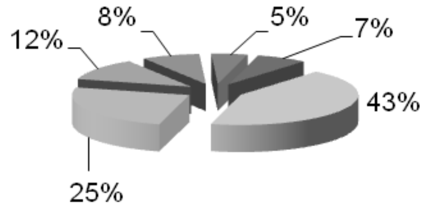

Fig. 2. Shares of non-conventional RES in the world (WECI forecast)

Biomass	-43%	Geothermal energy - 8%
Solar energy	-25%	Ocean energy - 5%
Wind energy	-12%	Micro hydropower - 7%

The main disadvantage of using biomass for energy purposes is that the energy produced by the technologies considered has a high cost and in most cases cannot compete with fossil fuels in the free market. Abroad these issues are addressed by subsidies for construction of energy facilities using biomass, as well as introduction of "green" taxes, i.e. development of this energy sector is based in Western countries on state support.

The scientific novelty of this work is the mathematical model proposed by the authors and substantiated by the authors for the efficient use of energy from different types of biomass in the global energy economy.

To study the possibility of extended use of biomass energy, a mathematical model was developed, the main elements of which are the information-energy network of the fuel and bioenergy balance (Fig. 3) and the database of bioenergy equipment.

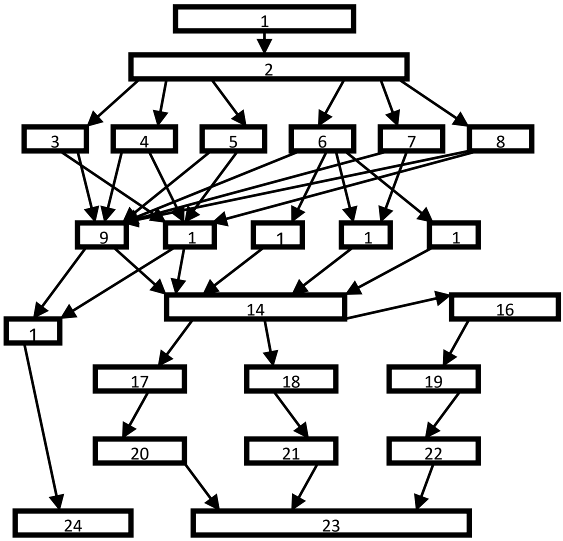

Fig. 3. Bioenergy balance information network Legend: *1* - biomass; *2* - transport and preparation; *3* - biomass of poultry complexes; *4* - biomass of pig complexes; *5* - biomass of cattle complexes; *6* - biomass of plant origin; *7* - organic part of municipal solid waste; *8* - municipal sewage; *9* - bioreactor-methanol; *10* - biofilter; *11* - pyrolysis; *12* - direct combustion; *13* - biomass gasification; *14* - biogas; *15* - micro-organic fertilizer; *16* - gas holder; *17* - biogas heat generator; *18* - electricity generator; *19* - autonomous biogas boiler; *20* - heat energy; *21* - electricity; *22* - heat energy; *23* - heat and electricity consumers; *24* - crop production

The generated information-energy network of fuel-bio-energy balance represents energy economy in the form of a set of objects of various types, exchanging energy flows. In the given scheme objects 3,4,5,6,7,8 are suppliers of commodity biomass to the world energy economy, and objects 23,24 are consumers of heat and electric energy as well as of microorganic fertilizers. The starting information for the study is data characterizing the energy balance by energy flow stages (extraction, processing, conversion, transport, storage, and end use).

The stages of the energy flow are represented in the nodes of the network. The lines connecting the nodes correspond to the energy flows between the respective nodes. Each type of node in the energy balance information network corresponds to its own computational unit in the form of a system of non-linear equations.

Several types of nodes are used in the energy information network, as shown in (Fig. 3): energy resource, transformation, reserve, decision, demand, nodes with many outputs and nodes with many inputs.

If we talk about Ukraine, a number of laws and programs (the Law of Ukraine N555-IY of 20.03.03) were adopted for the state support of activities and technologies based on biomass energy use. "On Alternative Sources of Energy", the Presidential Edict N1094/2003 "On Steps to Develop Bioenergy Fuel Production", National Energy Program of Ukraine till 2010, the Program of state support for the development of alternative and renewable energy sources and small hydro and heat energy technologies, etc.). However, the legal framework does not solve the overall problem due to the lack of funding sources, i.e. the search for processes and technologies with low capital and operational costs and low prime cost of the energy products obtained is relevant for Ukraine.

The main difficulties in the use of waste biomass as fuel in the existing energy units arise because of the different granulometric and chemical composition of biomass. The low bulk density makes the transport of biomass waste from the place of production to the consumer unprofitable, and the high volatile yield makes it difficult to combust biomass in the furnaces of existing energy units.

Thus, in Ukraine, the energy use of biomass is most promising for industrial enterprises (oil extraction plants, furniture factories, etc.) that produce significant amounts of biomass waste as a result of their main production. In this case, the economic effect of energy use is mainly determined by the capital costs of the equipment. In this case, the reconstruction of existing energy and energy processing equipment, allowing the use of biomass as fuel, is undoubtedly a more efficient direction compared to the installation of a new unit. This is especially true if the possibility of using fossil fuels as a reserve fuel remains [1,2].

Additional economic benefit from the energy use of biomass can be obtained by developing integrated technologies that give the possibility to obtain, in addition to the production of energy products, a product that is liquid on the market, e.g. carbon material, organic fertilizers, etc.

Analysis of biomass energy potential in Ukraine (Fig. 4) [1,14-16], conducted by the Institute of Technical Thermophysics of National Academy of Sciences of Ukraine and Scientific and Technical Centre "Biomass", showed that the share of industrial biomass waste is about 30% of the total biomass potential.

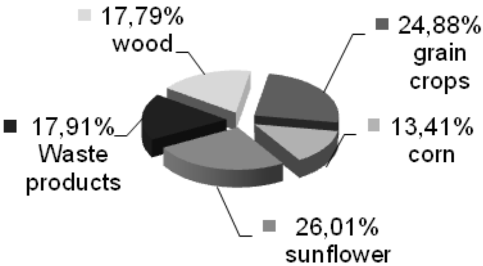

Fig. 4. Energy potential of biomass in Ukraine

Currently, biomass in Ukraine covers about 0,5% of its primary energy needs (~1 million tce) [3].

Presence of biomass fuel potential in Ukraine requires analysis of the existing technologies of its energy use, first of all, from the ecological point of view, including determination of the specific emission of greenhouse gases. The latter is especially topical in the implementation of projects under the Kyoto Protocol.

The choice of technology is determined by properties of different types of biomass as energy fuel. The calorific value of most types of biomass waste is within the range of 13-19 MJ/kg [1,14-16,20]. The main influence on the calorific value is the moisture content of the fuel [18,19].

The presence in biofuels of impurities such as chlorine (in wood - 0,1 %, in straw - up to 0,75 %) [1, 18, 19] reduces its quality which is compensated by a low sulphur content (0,2-0,77 %) [1], compared to domestic coal (*Sp*=2-3 %).

The ash content in biomass depends on time of year, soil, climate, etc. The real ash content of wood fuel including storage and transport reaches 1,5-2 % due to wood contamination. The ash content of biomass in the form of straw from different crops, sunflower husks, rushes, needles, etc. exceeds that of wood and is mostly in the range of 3-7 % [1,2], and ash content of rice hulls can reach 20 % of the fuel working mass.

The shape and size of the particles which make up the biomass waste have a great influence on the way they are used. The dispersion composition of the particles is also important. In the case of organic waste, we are usually dealing with materials consisting of finely dispersed particles of different shapes and with low bulk density (120-260 kg/m^3) [1,3,20]. Chemical composition of biomass waste causes high volatile matter yield when heated (70-75 %). These features of biomass waste have to be considered when choosing and improving technologies and equipment for their use for energy purposes.

Theoretically, depending on the moisture content, biomass is processed by thermochemical or biological methods. Biomass with low moisture content (agricultural and municipal solid waste) is processed using thermochemical processes: direct combustion, gasification, pyrolysis, liquefaction, hydrolysis. Biomass with high moisture content (sewage, municipal waste) is recycled using biological processes.

In practice, the following methods of processing biomass for energy production are used:

- direct combustion for direct production of heat;
- gasification of biomass;
- pyrolysis (dry distillation), aimed at obtaining the maximum gaseous fuel (mainly hydrogen and CO). The producer gas has a calorific value of 4-8 MJ/m^3;
- alcohol fermentation to produce ethyl alcohol (ethanol) from biomass
- alcohol (ethanol);

- anaerobic digestion, which is the most promising
- means of obtaining fuel from organic matter.

Estimated calculations made in (Fig. 4) show that in Ukraine a large amount of biogas can be obtained annually from the manure if it is fully processed by bioconversion.

When assessing the economic efficiency, it should be taken into account that the biogas plant provides simultaneous decontamination of manure and fertilizer production. It is also part of a system of environmental protection measures. In this case, biogas plants will always have a positive effect on the economy.

Biogas is also produced from municipal (cities and urban-type settlements) wastewater. Its output is 0,001 m^3 per 1m^3 of waste water.

The following anaerobic methane digestion regimes are known: psychophilic (digestion temperature °C), mesophilic (°C) and thermophilic (°C).

METHODOLOGY FOR DETERMINING THE ENVIRONMENTAL EFFICIENCY OF BIOENERGY FUEL USE

1. Environmental criteria for assessing the energy use of biogas

One of the main goals of biogas energy use, as mentioned above, is to reduce greenhouse gas emissions when replacing fossil fuels. This implies determining emissions before and after biogas use. The determination of emissions is based on a systematic approach, when the calculation is made taking into account emissions from fuel extraction, transportation, fuel consumption for equipment manufacturing, etc. At the same time, the life cycle of equipment and capital facilities is considered [72,147,183].

As a rule, these methods allow determining emissions in relation to specific technologies and equipment, as well as fuel types. As a result, the following are determined:

- is the absolute value of emissions for the considered period of time $K_{CO_2}\left[gCO_2 - \frac{eq}{hour}\right]$,
- emission rate (given emission) referred to a unit of feedstock - $k_{CO_2}\left[q\mathrm{CO}_2 - \frac{eq}{J}\right]$ or $e_{CO_2}\left[q\mathrm{CO}_2 - \frac{eq}{m^3}\right]$.

❖ specific emission E_y per unit of useful energy $\left(q\mathrm{CO}_2 - \frac{eq}{hour}, q\mathrm{CO}_2 - \frac{eq}{Gcal}\right)$.

These indicators allow us to estimate the reduction of emissions from the production of the same type of energy. However, comparing these indicators in the production of different types of energy is not objective. In addition, the obtained indicators are not direct characteristics, but are indirect. Thus, the adopted emission reduction indicators do not allow for an objective comparison of different technologies and equipment, the efficiency of using different types of biofuels and assessing the impact of their quality on the final result, as well as fully taking into account the impact of the type and quality of the substitute fuel.

At the same time, the amount of biogas that can be used for energy purposes is limited. For example, according to estimates of [7, 130], the amount of biogas that can be used for energy purposes is 9,07 million tons of equivalent fuel per year, which does not exceed 4,6% of primary energy consumption in the country. This potential should be utilized with maximum efficiency.

In this regard, the development of performance indicators for the ecological use of biofuels is becoming relevant from this point of view.

The above-mentioned developments are computer programs with corresponding databases. One of the peculiarities of using these programs, in our opinion, is that, on the one hand, they allow for a specific calculation with maximum detail and assessment of the "integral" result. At the same time, the analysis of the interaction of various factors remains hidden, which can often lead to erroneous conclusions. This is especially true for generalizing (strategic) analysis. Therefore, computational studies should be supplemented by analytical studies that allow us to identify the main relationships between parameters.

This is the approach we used to develop the indicator of specific greenhouse gas emission reduction when replacing fossil fuels with biogas - k_{CO_2} [147].

$$k_{CO_2} = \frac{K^{N.F.} - K^{BG}}{B_{BG} * Q^{R}_{NF}}$$

where $k^{N,F}$,k^{BG} is the absolute value of greenhouse gas emissions when operating on natural fuel and biogas, respectively, kg $q\mathrm{CO}_2 - \frac{eq}{hour}$;

B_{EG} - biogas consumption, m^3/hour;

Q_{NF}^{R} - is the calorific value of biogas, J/m^3.

The determination of greenhouse gas emissions is based on the use of the emission factor [kg CO_2 eq/kg], which is an unambiguous characteristic of a given fuel type. Then the absolute value of emissions can be calculated according to the following equation

$$K = B \cdot e_{\mathrm{CO}_2}, \quad (2)$$

where B - is fuel consumption, m/hour^3

In turn, fuel consumption is determined by the performance of the power unit and its efficiency - η_Σ

$$B = \frac{Q_u}{Q_N^R \cdot \eta_\Sigma},$$

Assuming that useful energy Q_u production is the same before and after the replacement of natural fuels and taking into account expressions (4.2) and (4.3), the form of the dependence for determining the specific reduction of greenhouse gas emissions - $\varepsilon_{\mathrm{CO}_2}$ (1) will be transformed into an expression that does not contain useful energy

$$k_{CO_2} = k^{N.F.} * \frac{\eta_\Sigma^{BG}}{\eta_\Sigma^{N.F}} - k^{BG},$$

where, $$k^{N.F.} = \frac{e_{CO_2}^{N.F.}}{Q_{N,NF}^R}; \qquad k^{BG} = \frac{e_{CO_2}^{BG}}{Q_{N,BG}^R}.$$

Thus, the main parameters that affect the efficiency of biogas use to reduce greenhouse gas emissions when replacing fossil fuels are:

- greenhouse gas emission rates per unit of calorific value of fuel, $k^{N,F}$, $k^{B,G}$ similar to [2-6];

- the ratio of the efficiency of energy units before and after the replacement of natural fuel, whereby the gross efficiency is the total efficiency of energy consumption for own needs and losses (including biogas pretreatment).

In the case of co-combustion of biogas and natural fuel, with its partial replacement, the dependence for calculation will be transformed to the form

$$k_{CO2} = \left(k^{N.F.} \cdot \frac{\eta_{\Sigma}^{M}}{\eta_{\Sigma}^{N.F.}} - k^{M} \right) \cdot \frac{1}{(1-a')},$$

where $$k^{M} = \frac{e_{CO_2}^{M}}{Q_{N,M}^{R}} = \frac{e_{CO_2}^{N.F..} \cdot a + e_{CO_2}^{BG}(1-a)}{Q_{N,N..F}^{R} \cdot a + Q_{N.BG}^{R}(1-a)},$$

a - mass fraction of natural fuel in the mixture;

a' - the energy share of natural fuel in the mixture is equal to

$$a' = \frac{Q_{N,NF}^{R}}{Q_{N,M}^{R}}$$

As is well known, the value of efficiency is determined by the technical level of the equipment and energy conversion technology used, both when burning natural fuels and biogas. In addition, the value of efficiency is also related to the efficiency of equipment use over time, which is especially important in the case of co-generation of heat and electricity.

A special place is occupied by the case of partial utilization of the energy potential of biogas, for example, when using anaerobic fermentation technology. In this case, the shaved residue can be used as a material for technological needs (production of high-tech fertilizers). Accordingly, in expression (4), the efficiency of a power unit operating on biogas should take into account the heat losses during anaerobic fermentation, and the calculation of the emission factor should be made in relation to the combustion of volatile products of this process.

A systematic approach to determining the value of the emission indicator, similar to [183], includes summing up greenhouse gas emissions along the entire technological chain of fuel use, from extraction to combustion. Thus, the structure of the emission indicator for any type of fuel consists of four main components: emissions from fuel extraction - k^{prod}, its transportation - k^{tr}, processing - k^{proc}, fuel combustion - k^{com}. Then the general type of dependence for calculating the emission factor can be represented as the sum of

$$k = k^{prod} + k^{tr} + k^{proc} + k^{com}, \tag{8}$$

Graphically, this dependence for natural fuels is shown in the diagrams (Fig. 1,2). Thus, the value of the emission indicator depends on the national characteristics of the energy complex of each country (availability of own fuel resources, structure and characteristics of the energy and mining industries, territorial location, etc.) Below are the methods for determining the emission factor for the main types of fossil fuels and biogas in relation to the conditions of Ukraine.

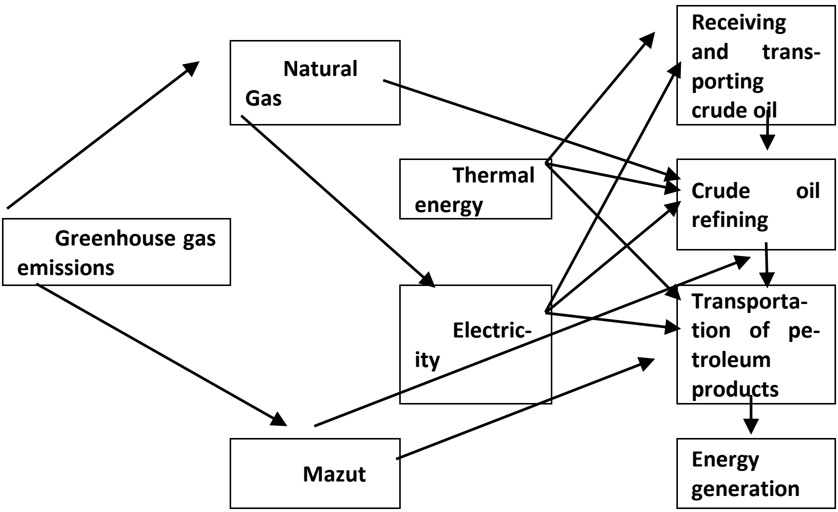

Fig. 1. Scheme of calculation of greenhouse gas emissions from natural gas combustion

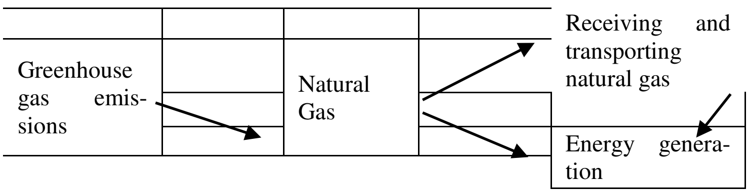

Fig. 2. Scheme for calculating greenhouse gas emissions from fuel oil combustion

2. Methodology for calculating emission indicators for biogas production by anaerobic digestion of biomass

The greenhouse gas emissions from anaerobic digestion of biomass for energy are related to emissions from the combustion of fossil fuels at the stage of collection, processing and. Given that biomass suitable for energy use in Ukraine is treated as a waste product, greenhouse gas emissions associated with harvesting and collection of biomass were not taken into account, as energy consumption was fully attributed to the production of the main product. In this case, the emissions figure for biogas k_{CO_2} consists of two components

$$k_{CO2}^{BG} = k_{ferm}^{BM} + k_{proc}^{BM}, \quad (9)$$

where k_{ferm}^{BM}- $g[CO]_{\downarrow}2-eq/kg$ of biogas equivalent).

k_{proc}^{BM} - greenhouse gas emissions are related to the fermentation process (unloading and loading of biomass, as well as mixing costs), $g[CO]_{\downarrow}2-eq/kg$ of biogas equivalent).

Biofuel production processes using anaerobic fermentation include electricity costs for unloading, loading, and mixing biomass, as well as heat for substrate preparation and thermal stabilization of reactors. Electricity consumption for these types of processes is summarized in Table 1 [184].

Table 1

Specific electricity consumption in anaerobic biomass fermentation [184]

Type of equipment used	Pumps for loading and unloading	Stirrers in the reactor	Other process equipment
Electricity consumption (for a Danish reactor with a volume of 800 $m^{3}$of biomass) b_{ee}^{BM}, kWh/t	5-12	5-7	3-5
Electricity costs (for small farms) installations of 130-150 $m^{3}$of biomass) b_{ee}^{BM}, kWh/t	2-4	1-3	0,5-2

Accordingly, the greenhouse gas emissions associated with biomass chipping and anaerobic digestion of biomass were determined by the following dependencies

$$k_{CO_2}^{BG} = b_{ee}^{procBM} * E_{ee} + b_{ee}^{fermBM} * E_{ee}$$

The processes of preparing biomass as an energy fuel include two alternative processes: shredding and pressing (briquetting). The energy consumption for shredding depends on the finite size of biomass particles and the type of biomass in Table 2 [184].

Table 2

Specific electricity consumption during biomass grinding [184]

Particle size, mm	>25	>15	>10	>5	>3
Specific energy consumption $b_{ee}^{chip\ BM}$, kWh/t	10-25	20-5	25-45	40-80	60-130

Accordingly, the greenhouse gas emissions associated with biomass chipping were determined by the following dependence

$$k^{chipBM} = b_{ee}^{chipBM} * E_{ee} \qquad (11)$$

In the case of further pressing and pelletizing, biomass can be pressed and pelleted using several well-known processes, the name of which determines the type of equipment used [150,152]. Electricity consumption directly for biomass pressing is 20-70 kWh/t (Table 3) [12,154].

Table 3

Energy consumption during briquetting and pelletizing of biomass

Type of used equipment	Rolling press	Screw press
Electricity consumption $b_{ee}^{pres\ BM}$, kWh/t	20-60	50-70

Accordingly, the greenhouse gas emissions from biomass pressing include emissions associated with the use of electricity

$$k^{pres\ BM} = b_{ee}^{presBM} * E_{ee}, \qquad (12)$$

Then the total greenhouse gas emissions for biomass preparation and processing are equal to

$$k_{proc}^{BM} = k^{presBM} + k^{chipBM}, \qquad (13)$$

The above methodology made it possible to estimate greenhouse gas emissions for different types of natural fuels and biomass, on the basis of which various options for biomass energy technologies and equipment were compared.

3 Determination of the emission factor for natural gas use

Due to the fact that the share of imported natural gas used in Ukraine exceeds 80% of the gas consumed in 2007-2019 [150, 183], the calculation of the emission indicator took into account energy consumption only for gas transportation and its use in power units.

Ukraine has a developed gas transportation system with a length of 36,7 thousand km, which includes 72 compressor stations [161]. The system's inlet capacity is 290 billion m^3 per year. The gas transportation system provides gas supply to domestic consumers and transit of Russian natural gas to European countries. Over the past 10 years, the volume of natural gas transit has amounted to 113-137 billion m^3 per year. Intensive operation of the gas transportation system has led to the need to reconstruct and replace pipelines and compressor equipment. More than a third of gas pipelines have been in operation for 23 to 48 years. A significant number of gas pumping units have low technical performance (efficiency), resulting in gas transportation costs of 5%-6% of the transported gas [161, 183]. Thus, the specific consumption of natural gas for its transportation is b_{TR}^{NG} =0,05-0,06 kg per t/kg per p. The greenhouse gas emissions during the transportation of natural gas k_{TR}^{NG} were determined based on the conditions of fuel combustion in gas pumping units

$$k_{TR}^{NG} = b_{TR}^{NG} * k_{cf}^{NG}, \qquad (14)$$

where k_{cf}^{NG} - indicator of emission during combustion of natural gas which is calculated according to dependence (4.15), $g[CO]_{\downarrow}2-eq/kg$ of fuel equivalent).

In this case, fuel combustion means either direct combustion in different types of furnaces or after thermal processing (anaerobic fermentation, pyrolysis, gasification) with subsequent combustion of the processing products in power units: boilers, engines, gas turbines.

Using the values of specific emission, $э_{CO_2}, э_{N_2O}, э_{CH_4}$, the greenhouse gas emissions from fuel combustion k^{cf}were calculated according to the following dependence

$$k^{cf} = э_{CO_2} + GWP_{CH_4} э_{CH_4} + GWP_{N_2O} э_{N_2O}, \quad (15)$$

where GWP_{N2O} -is the conversion factor of N_2O to CO_2 - equivalent, equal to 310 [10];

GWP_{CH4} - is the conversion factor of methane to CO_2 - equivalent (Global Warming Potential), equal to 21 [10];

$э_{CH4}, э_{H2O}$ - Specific emissions of nitrous oxide and methane from fuel combustion in in the process units gCN_4 /kg of fuel oil and gN_2O/kg of fuel oil, respectively.

In case of direct combustion of fuel in boiler furnaces, the data in Table 4.4 can be used to determine the specific emissions.

Table 4

Values of specific emissions of CO_2, N_2O and CH_4 from fuel combustion in Ukraine emissions from fuel combustion in Ukraine

Type of fuel	Fuel oil	Natural gas
$э_{CO2}$, CO_2 г/ кг у.п	2281-2353	1527-1669
$э^{ээ}_{CH4}$, CH_4 г/ кг у.п	0,237-0,0281	0,143-085
$э^{ээ}_{N2O}$, N_2O г/ кг у.п	0,261-0,083	0,227-0,084

The total greenhouse gas emissions for natural gas use are as follows

$$k^{NG} = k^{NG}_{cf} + k^{NG}_{TR} \quad (16)$$

4. Determination of the emission factor for biogas use

The study of environmental efficiency of energy technologies requires knowledge of emission indicators for both main types of fossil fuels and bioenergy fuels. Due to the lack of necessary data in the national literature on the conditions of Ukraine, the study developed atic approach

Analyzing the dependence of the specific reduction in greenhouse gas emissions

$$\varepsilon_{CO_2} = k^{N.F.}\left(\frac{\eta^{BioG}_{\Sigma}}{\eta^{N.F.}_{\Sigma}} - \frac{k^{BioG}}{k^{N.F.}}\right), \quad (17)$$

where $\frac{k^{N.F} = Э^{N.F}}{Q^R_{N.N.F}}$; $\frac{k^{N.F} = Э^{N.F}}{Q^R_{N.N.F}}$; $\frac{k^{BioG} = Э^{BioG}}{Q^R_{N.BioG}}$

which shows that it is determined by three quantities: the ratio of emission rates and efficiency of energy units, as well as the absolute value of fossil fuel emissions.

Using the developed methodology, quantitative data on the change in greenhouse gas emissions k_{CO2} for the conditions of Ukraine have been determined, which amounted to:

when burning gasoline - 2188÷2329), $g[CO]_{\downarrow}2-eq/kg$ of fuel oil);

when burning fuel oil - 2414÷2552), $g[CO]_{\downarrow}2-eq/kg$ of fuel oil equivalent);

for natural gas combustion - 1712÷1910), $g[CO]_{\downarrow}2-eq/kg$ of fuel equivalent);

for biogas combustion, anaerobic digestion of biomass - 1037÷1253), $g[CO]_{\downarrow}2-eq/kg$ of fuel equivalent).

Based on the calculated data on greenhouse gas emissions for the main types of fossil fuels in Ukraine (Table 5), and comparing the value of biogas combustion emissions $k^{BioG}_{CO_2}/k^{grh}_{CO_2}$ the ratio varies in the range of 0,29-0,65. For each type of natural fuel, the value of this ratio is given in Table 6 and in [148].

Table 5

Greenhouse gas emissions for the main types of fossil fuels in Ukraine

Type of fuel		Petrol		Fuel oil		Natural gas	
		g[CO] of fuel oil)	%	g[CO] of fuel oil)		g[CO] of fuel oil)	%
m_{max}	k^{prod}	1,88	0,1	1,87	0,1	-
	k^{tr}	2,03	0,1	2,95	0,1	93,4
	k^{proc}	147,3	6,5	147,3	5,6	-
	$k^{трнп}$	65,3	2,7	19,0	0,7	-
	k^{com}	2113	90,6	2381	93,2	1817
	k	2329	100	2552	100	1910
m_{min}	k^{prod}	1,39	0,1	1,4	0,1	-
	k^{tr}	0,1	0,0	0,1	0,0	72,8
	k^{proc}	75,1	3,5	75,4	3,4	-
	$k^{трнп}$	1,2	0,0	-	-	-

	k^{com}	2111	96,4	2338	97,3	1639
	k	2188	100	2414	100	1712

Given that the ratio of efficiency coefficients in dependence (17) does not differ much from one, it can be argued that the amount of greenhouse gas emissions from biomass can change the final result by 3-7%.

Table 6

Values of the ratio of biogas emissions from anaerobic digestion and natural fuels, $k^{BioG}/k^{N,F}$

Type of replacement fuel	coal	petrol	fuel oil	diesel fuel	natural gas
Maximum value	0,3	0,54	0,49	0,47	0,65
Minimum value	0,29	0,47	0,41	0,42	0,6

Using the obtained values of emission indicators (Table 5 and Table 6) for natural gas and biogas obtained from anaerobic digestion of biomass, the values of specific greenhouse gas emissions in the production of thermal Pk_{tem} and electric energy Pk_{ee} in Ukraine were determined according to the following dependencies

$$Pk_{ee} = k * b_{ee}\, ;\, Pk_{tem} = k * b_{tem}\, , \tag{18}$$

The values of specific fuel consumption for heat production were based on the passport indicators of boiler equipment offered on the Ukrainian market, as well as data from prototypes of boiler units converted to bioenergy fuel (Table 4.7), and the values of specific emissions are also given there.

Table 7

Characteristics of hot water boilers

Heat output	Type of fuel	Efficiency	Specific fuel consumption, kg of fuel equivalent/Gcal	Specific greenhouse gas emissions, $Pk_{\tau ev}$, $kgCO_2$ -eq/Gcal
Up to 10 kW	natural gas	84-2	169-152	322,1-260,4
Up to 10 kW	biogas	70-88	177-159	232,8-194,3
Up to 100 kW	coal	77-84	185-170	804,7-571,9
Up to 100 kW	natural gas	84-92	170-155	324,4-265,7

Based on the efficiency values of hot water boilers fired by fossil fuels and biogas produced by anaerobic digestion, the values of specific greenhouse gas emissions from heat Pk_{tem} production in Ukraine were determined. Based on the efficiency values of hot water boilers with a capacity of up to 10 kW, operating on natural gas and biogas obtained from anaerobic digestion (Table 4.7), it is necessary to assume that the ratio $\eta_{\Sigma}^{BioG} / \eta_{\Sigma}^{N.G}$ can vary from 0,833 to 0,956.

The data shows that the efficiency of power units significantly affects the result of replacing fossil fuels with biogas produced by anaerobic digestion.

It is interesting to analyze the co-combustion of natural gas and biogas produced by anaerobic digestion. With partial replacement of natural gas with biogas produced from anaerobic digestion, the emission rate for the fuel mixture decreases in proportion to the share of biogas (Fig. 4.3).

When modeling the operation of boilers with a capacity of up to 10 kW with partial replacement of natural gas with biogas produced by anaerobic digestion, these factors were taken into account. The results of the calculations showed that the change in boiler efficiency is not significant up to 3% (Table 8). The actual experience of co-combustion of natural gas with biogas produced from anaerobic digestion confirms the results of a slight change in boiler efficiency [142, 144].

Table 8

Performance of boilers with partial replacement of natural gas with biogas obtained from anaerobic digestion of biomass

The mass share of natural gas in mixtures with biogas	0,6	0,8	1
Boiler efficiency, %	85,2	85,6	87,9
$\eta_{\Sigma}^{CM} / \eta_{\Sigma}^{N.G}$	0,969	0,974	1
k_{CO2} max, $q[CO]_{\downarrow} 2 - eq / kg$ of fuel oil),	1646,0	1777,0	–
k_{CO2} min, of $q[CO]_{\downarrow} 2 - eq / kg$ fuel oil),	1443,2	1578,6	–

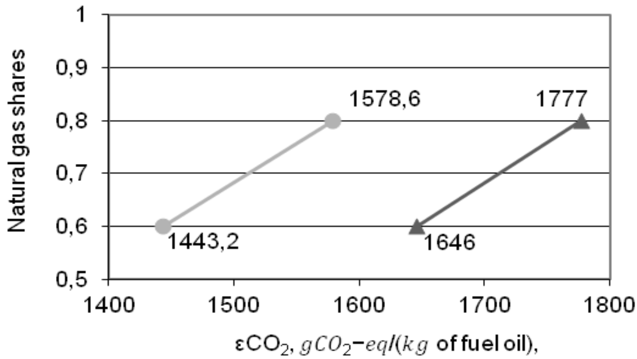

Fig. 3. The value of the emission factor ε_{CO_2} depending on the energy share of natural gas when co-combusted with biogas

All of the above demonstrates the relevance of the development of bioenergy fuel combustion technology obtained from anaerobic digestion of biomass and further research in this area.

5. Conclusions

1. A methodology has been developed that allows analysing the environmental efficiency of energy use of biogas obtained from anaerobic digestion of biomass based on the specific reduction k_{CO_2}. This indicator makes it possible to objectively compare existing and proposed technologies and equipment for the use of bioenergy fuels, while fully taking into account the complex impact of the type and quality of the substitute fuel on the emissions and efficiency of thermal units.

2. Using the developed methodology, quantitative data on the change in greenhouse gas emissions k_{CO_2} for the conditions of Ukraine were determined, which amounted to:

- for gasoline - 2188÷2329 g_{CO_2} - eq/kg of fuel oil),

- fuel oil - 2414÷552 g_{CO_2} - eq/kg of fuel oil equivalent,

- natural gas - 1712÷1910 g_{CO_2} - eq/kg fuel oil equivalent,

- combustion of biogas produced by anaerobic digestion of biomass - 1037÷1253 g_{CO_2} - eq/kg fuel oil equivalent.

3. On the basis of the performed studies, the ranges of possible specific reduction of greenhouse gas emissions when replacing natural gas with bioenergy fuel obtained from anaerobic digestion of biomass were determined. The value can vary when replacing (60% of natural gas and 40% of biogas) in the range of 1443,8÷1646,0 g_{CO_2} - eq/kg of fuel oil equivalent, and when replacing (80% of natural gas and 20% of biogas) in the range of 1578,6÷1777,0 g_{CO_2} - eq/kg of fuel oil equivalent equivalent.

2. Development of a methodology for determining the value of greenhouse gas emission indicator of greenhouse gases under conditions of Ukraine

A systematic approach to determining the value of the emission indicator, similar to [13-16,68], includes the summation of greenhouse gas emissions throughout the technological chain of fuel use, beginning with the extraction and ending with its combustion. Thus, the structure of the emission indicator for any fuel consists of four main components: emission during fuel production - $e_{CO_2}^{prod}$, its transport - $e_{CO_2}^{transp}$, recycling - $e_{CO_2}^{proc}$, fuel combustion - $e_{CO_2}^{comb}$. The general form of the relationship for calculating the emission factor can then be represented as the sum of

$$e_{CO_2} = e_{CO_2}^{prod} + e_{CO_2}^{trasp} + e_{CO_2}^{proc} + e_{CO_2}^{comb} \qquad (2.7)$$

In this calculation, all the main energy carriers (fuels, heat and electricity) used in all the technological steps are taken into account.

Graphically this dependence for different fossil fuels is shown in figures 2.1, 2.2, 2.3.

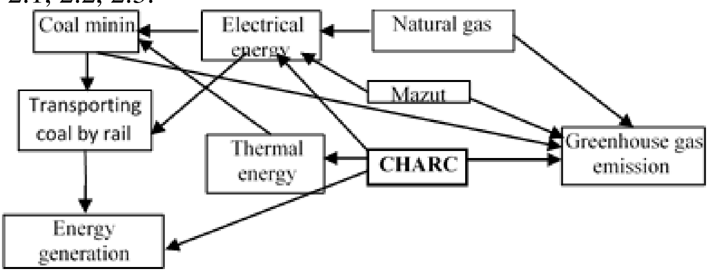

Figure 2.1. Schematic diagram for calculating the greenhouse gas emission index

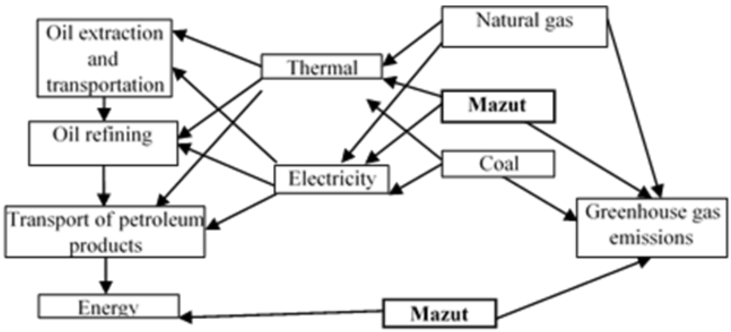

Figure 2.2. Calculation scheme of the greenhouse gas emission index

emissions from fuel oil combustion

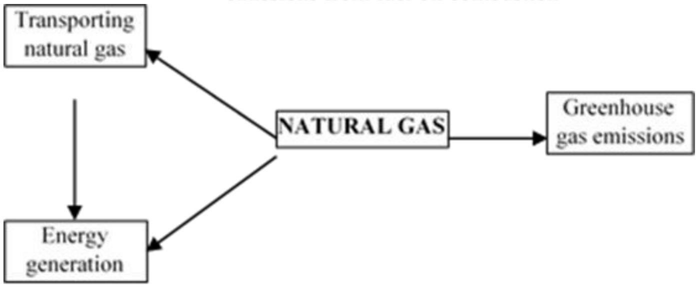

Fig.2.3 Calculation scheme for reduced greenhouse gas emissions emissions from natural gas combustion

Thus, the value of the emission indicator depends on the national characteristics of the energy complex of each state (availability of own fuel resources, structure and characteristics of the energy and extractive industries, territorial location, etc.). Below the methodologies for determining the emission index for the main types of fossil fuels and biomass in relation to the conditions of Ukraine are given.

2.2.1 Methodology for determining greenhouse gas emissions from coal combustion under Ukrainian conditions.

Coal production in Ukraine is carried out mainly by underground mining (about 99% [86]). In this regard, when developing the algorithm, we used the data on electricity and heat consumption typical for this method of mining, with regard to the conditions of the Donetsk coal basin, where more than 80% of domestic coal is mined. The main sources of greenhouse gas emissions from coal mining are electricity and heat consumption and methane emissions from mine ventilation and degassing. Accordingly, the reduced greenhouse gas emissions from coal mining $e_{CO_2}^{prod}$ have been determined using the relationship

$$e_{CO_2}^{prod} = b_{Tem}^{y} E_{Tem} + b_{ee}^{y} E_{ee} + э_{CH4}^{m} + GWP_{CH4} + э_{CO_2}^{m}, \qquad (2.8)$$

where is E_{Tem} specific greenhouse gas emission in thermal energy generation, $kgCO_2$-eq/Gcal;

E_{ee}- specific greenhouse gas emission in electricity generation, $kgCO_2$-eq/kWh;

$GWP_{CH\,4}$ - methane-to-CO_2-equivalent conversion factor (Global Warming Potential) equal to 21[87];

$э_{CH4}^{m}$ - mine methane emission factor, gCH_4/kg CO;

$э_{CO_2}^{m}$ - is the carbon dioxide emission rate from combustion of excess of coal mine methane, gCO_2/kg teq;

b_{Tem}^{y}, b_{ee}^{y} - specific heat and electricity consumption during coal extraction, kWh/kg fuel equivalent (Gcal/kg fuel equivalent).

The methodology for determining specific greenhouse gas emissions associated with the use of heat and electricity, and taking into account the structure of electricity production and fuel consumption, as well as losses during transportation, is given in Annex A.

The main electricity consumption in coal mining is related to mine ventilation, lifting, dewatering, underground transport port operation, compressed air production and lighting. Depending on the production technology and the mining conditions, the specific electricity consumption may vary by several times [88-92]. Additionally, the specific power consumption increases due to the high ash content of coal mined in Ukraine and consequently its low calorific value.

The real range of possible values of specific electricity consumption in coal mining is as follows: the minimum value of energy consumption typical for mines of the State Holding "Pavlogradugol" - b_{be}^{y} =22,1 kWh/t (0,04 kWh/kg t) [90], maximum value - for Production Association "Artemugol" - b_{be}^{y}=459 kWh/t (0,647 kWh/kg t) [91]. The average value of specific electricity consumption for the industry for the year 2000 b_{be}^{y} is =105,2 kW·h/t (0,1837 kW·h/kg t).

In contrast to electricity, which accounts for 20-50 % of the cost of coal, the consumption of thermal energy has attracted less attention from coal producers. This is primarily due to the fact that heat is produced in own boiler-houses from their own coal and thus the costs of this type of energy are much lower and up to now there is no standardised metering system in place. This significantly reduces the reliability of information on heat consumption during coal extraction.

At the same time it is known, that specific heat consumption by pre-mining of coal in the period of the planned economy was in 1985 - 1990 b^{y}_{Tem} =25-26 kcal/kg (or taking into account the quality of coal mined in Ukraine 38-39 kcal/kg fuel equivalent) [114]. These data can be taken as the lower bound of the energy input range. The upper limit, as in the case of power consumption, exceeds the lower limit by several orders of magnitude, and on data for 1997 at the Artemugol production association was b^{y}_{Tem} =220 kcal/kg (310,2 kcal/kg resistivity), and at Kirovskaya mine b^{y}_{Tem} -567 kcal/kg (799,0 kcal/kg resistivity).

Methane emissions from underground coal mining are associated with the need to ventilate and degasify coal seams to prevent explosions. Sources of methane are [84]:

- ventilation systems (methane concentration 0,2-1 %);
- vertical pre-degasification wells from the surface (methane concentration 80-90%);
- vertical wells from the surface at the waste sites (methane concentration 20-60%);
- horizontal and inclined underground degassing wells (methane concentration 20-60%).

In addition, methane emission does not stop even after the liquidation of mines [116]. For example, in the abandoned Tsentralnaya-Pervomayskaya mine, methane has been emitted for about 20 years. At the same time the efficiency of utilisation of mine methane is very low. According to different estimates [117 118] the share of utilized methane does not exceed 4-8 % of total emissions. The absolute quantity of methane emitted per year amounts to 2,1-2,428 bcm m^3, of which, according to [118], 80% is related to ventilation units, and around 20% - to de-gasification units. Part of the methane produced by the degassing units (200-207 million m^3/year) is used in boilers, and also for fueling vehicles, and the rest is combusted in flares. Thus, 80% of the mine methane from the ventilation units is emitted into the atmosphere, plus an additional 12% of the methane from the combustion in the candles. Considering the balance of coal mine methane and the quality of domestic coals the specific emission of coal mine methane is $э^{m}_{CH4}$ =34,9 gCH_4/kg t, and the specific emission of CO_2 from combustion of coal mine methane in a fuel candle is $э^{m}_{CH_2}$ =0,01 gCO_2/kg t.

The high ash content of coal mined in Ukraine implies enrichment before transportation, which requires additional energy costs.

The status quo [104] is that more than 50% of steam coals and more than 10% of anthracites go to power plants bypassing beneficiation plants. The rest of the coal is enriched. The enriched coal is mainly supplied to the metallurgical and municipal sectors. From enrichment plants the CHPPs get small fractions of the enriched coal with A^d=22 %, dry elimination of small fractions with ash content corresponding to the rank coal, intermediate products and slime with ash content A^d=39-45 % [104]. In this regard, the energy consumption for enrichment cannot be fully attributed to coal used in the energy sector, so it was not taken into account in the calculation of greenhouse gas emissions.

The lack of major rivers in the area of the Donetsk coal basin and the developed railway network in Ukraine (more than 22500 km [119]) have led to the fact that the main amount of coal is transported by rail. According to the Ministry of Transport, the share of transportation by electric traction exceeds 80% of the total turnover in Ukraine [120]. Therefore, when calculating greenhouse gas emissions during coal transportation, one hundred percent use of electric traction is assumed.

Electricity consumption and related greenhouse gas emissions are directly proportional to the distance of coal transportation S^{y}_{transp}[km]. The location of the Donetsk coal basin is such that the maximum distance of coal transportation within the borders of Ukraine does not exceed 1400 km [121], and the average specific power consumption taking into account the weight of the wagons (tare) according to [122] was 0,013-0,014 kWh/(t km gross) in 1995-1996. The characteristics of wagons used for coal transportation are given in Table 2.1 [123]. Thus, the weight of the transported coal is 25%-27% less than the weight of the railway stock. Correspondingly, specific power consumption increases by the same amount, compared to [122], and amounts to 0,0173-0,0187 kWh/tkm. Similar data given in [123] exceed the mentioned specific consumption twice, making 0,035-0,04 kWh/t km, and practically equal to the value of electricity consumption during coal transportation in Germany in 1990 - 0,03 kWh/(t km) [112].

Therefore, the unit electric energy consumption for coal transportation is 0,02-0,04 kWh/t km, or taking into account the averaged coal quality parameters in Ukraine b^{y}_{transp}=3,47·10-5 - 6,95·10-5, kWh/(kg tce(coal)·km). The greenhouse gas emissions from transport are then

$$e^{transp}_{CO_2} = S^{y}_{transp} * b^{y}_{transp} * E_{ee}, \qquad (2.9)$$

where b^{y}_{transp} - specific electricity consumption for coal transportation by rail, kWh/kg of fuel equivalent (coal)·km;

S^{y}_{transp} - transportation distance, km.

Table 2.1

Technical characteristics of wagons, used for coal transportation in CIS countries

Name	Indicator values			
Load capacity, *t*	62	63	93	125
Number of axles, *pcs*.	4	4	6	8
Tare, *t*	22,7	21,8	31,5	43,3
Gross wagon weight, *t*	84,7	84,8	124,5	168,3
Net/gross weight ratio, *t/t*	0,73	0,74	0,75	0,74

The greenhouse gas emission rate from coal combustion $e^{comb}_{CO_2}$ was calculated using the specific emission values, $э_{CO_2}$, $э_{CH_4}$, $_2$, $э_{CH_4}$, EMBED Equation.3 , according to the following relationship

$$e^{comb}_{CO_2} = э_{CO_2} + GWP_{CH4} + э_{CH4} + GWP_{N_2O} э_{N_2O}. \qquad (2.10)$$

In case of direct fuel combustion in flare boilers, specific emission values can be determined using data from Table A.4 of Annex A. In case of coal combustion in a suspended bed, no domestic data on greenhouse gas emissions are available, therefore foreign data [112], given in Table 2.2, can be used for calculations.

Table 2.2

Specific methane and nitrous oxide emissions from coal combustion in the suspended bed, kg/GJ

Installed capacity of TPP, MW	CH_4	N_2O
< 50	1	150
>50	5	100

Similar methodologies for calculating greenhouse gas emissions from refined products and natural gas are given in Annex *B* and Annex *C*, respectively.

General conclusions

1. Many countries of the world, including Ukraine, have significant potential for the production of biogas from manure of farm animals [1].

2. Mathematical model for efficient use of biomass energy in the global energy economy has been developed and justified that allows choosing the rational configuration of energy equipment and determining the optimal structure of energy consumption and costs of energy generation.

3. The absence of generalized data on the energy balance of biogas plants and methods of economic evaluation does not allow us to make an objective judgment about their efficiency, which hinders the involvement of millions of tons of agricultural animal manure into the national economy (Fig. 2).

4. The cause of climate change is greenhouse gases emitted into the atmosphere as a result of burning fossil fuels. The real ways to reduce these emissions is to conserve energy and to replace fossil fuels with non-conventional energy sources, the most potent at the moment, biomass. The main criteria for choosing a biomass energy technology are economic indicators and the amount of greenhouse gas emission reduction at the same amount of pollutants, such as sulphur oxides, nitrogen, carcinogens. Whereas the economic criteria are known and rather effectively used in practice, the ecological criteria do not permit to compare objectively the technologies and equipment which use different types of biofuel and do not enable to make full account of the influence of type and quality of substituted fuel.

5. The main reason for limiting the use of biomass for energy purposes in Ukraine is that the produced energy is relatively expensive, so it is relevant to look for processes and technologies with low capital and operational costs and low cost of energy production due

to production of co-products. Such technologies include the process of oxidative pyrolysis which allows getting fuel gas with relatively high calorific value, and also coke residue due to the sale of which one can get additional income.

6. One of effective directions of energy use of biomass, is the study of technology of organic processing of waste biomass, carried out in the bioenergy reactor. Preliminary studies allowed to determine the necessary technological parameters for creation of a pilot plant for organic processing of biomass waste. For further development of this process it is necessary to create a pilot plant, conduct experimental studies, determine the relationship of various technological parameters, including the use of mathematical modelling.

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