THE INFLUENCE OF BIOGAS CONTENT ON THE EMISSION OF HARMFUL IMPURITIES AND THE INTRODUCTION OF GREENHOUSE GAS EMISSION METHODOLOGY IN UKRAINE

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Abstract

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

In this regard, the development of performance indicators for the ecological use of biofuels becomes relevant from this point of view. The above-mentioned developments are computer programmes with relevant databases. One of the peculiarities of using these programmes, 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 generalised (strategic) analysis. Therefore, computational studies should be supplemented by analytical studies that allow identifying the main relationships between parameters.

The **scientific novelty** is as follows:

A methodology has been developed that allows analysing the environmental efficiency of energy use of biogas produced from anaer-

obic digestion of biomass based on the indicator of specific greenhouse gas emission reduction. This indicator allows an objective comparison of existing and proposed technologies and equipment for the use of bioenergy fuels, while fully taking into account the complex effect of the type and quality of the substitute fuel on the emissions and efficiency of thermal units.

Combustion kinetics calculations were carried out with the output of intermediate concentrations up to the time "τ"=0.5 s, when the burning process of the slowest components formed after the decomposition of hydrocarbon components is almost complete, and the CO_2 content in the combustion products is levelled and reaches a maximum. Thus, the processes occurring directly in the combustion zone are considered.

Based on the results of the computer calculations, we have constructed graphs (Fi. 1-3) that clearly illustrate the process of decomposition of the input and formation of new components. To avoid cluttering the figures, only the main reaction products (CO_2, H_2O, CO), as well as NO, NO_2 and components that affect their formation are shown in the graphs: NH, HCN, NSO, O, NO_2, CN.

Let's compare the results obtained for natural gas NG (see Fig. 2) and biogas without nitrogen-containing impurities, which corresponds to the composition of municipal wastewater digester gas BG (see Fig. 3). As can be seen from the graphs, 0.5 seconds before the end of the calculation, the carbon dioxide content reached 10.42% for GHG and 15.53% for BG, with CO2 concentrations continuously increasing to 10.3% (GHG, τ=0.05 s) and 16.52% (BG, τ=0.1 s), respectively, and then levelling off. A similar pattern is observed in the formation of H2O: a continuous increase to 18.24% (PG, τ=10-3s) and 17.24% (BG, τ=10-3s), followed by slow dissociation to 18.04% (PG, τ=0.3s) and 17.16% (BG, τ=0.5s).

The intensive formation of CO in NG begins at time τ=0.5·10^{-6}s and reaches a maximum of 7.27% at τ=0.5·10^{-5}s, followed by a rapid burnout to 0.13% at τ=0.05 s and then gradually decreases to 3.7·10^{-2} at τ=0.3 s. The process of CO formation in the BG is somewhat slower: a maximum of 4.41% is reached at τ=10^{-4}s, and by the time τ=0.3s, the CO content becomes 1.28·10^{-3}. The absolute content of CO during the combustion of BG, as we can see, is less than during the combustion of GHG until the time close to the end of the com-

bustion process by about an order of magnitude, which can be explained by the longer duration of the biogas combustion process.

Let's trace the formation of nitrogen oxides. The nature of the increase in nitrogen dioxide concentrations is the same for GHG and BG: at first, there is a slow increase to $3.05 \cdot 10^{-6}$ % at $\tau = 10^{-3}$ s for GHG and $3.86 \cdot 10^{-7}$ % at $\tau = 10^{-2}$ s for BG, and then there is a sharp increase by the time $\boldsymbol{\tau} = 0.3$ s to $2.69 \cdot 10^{-5}$ % for GHG and $1.81 \cdot 10^{-5}$ % for BG.
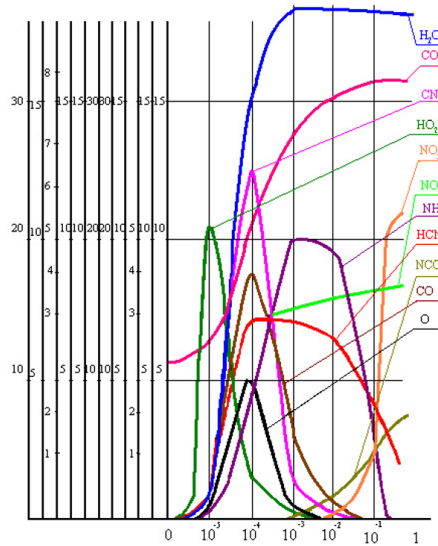

Fig. 1. Results of computer calculation of the kinetics of biogas combustion without nitrogen additives

This change in nitrogen oxide concentrations is explained by the "behavior" of NO_2 and O by the time nitrogen dioxide formation begins, the concentrations of peroxide reach a maximum of $3.66 \cdot 10^{-4}$ % at $\tau = 10^{-6}$ in PG and $1.04 \cdot 10^{-4}$ % at $\tau = 10^{-5}$ s in BG, then decrease by about an order of magnitude to $3.5 \cdot 10^{-5}$ % at $\tau = 0.5 \cdot 10^{-5}$ s in PG and $6.40 \cdot 10^{-6}$ % at $\tau = 10^{-3}$ in BG, and then by the time $\tau = 0.3$ the concentration decreases by another order of magnitude: to $6.2 \cdot 10^{-7}$ % for GHG and $1.05 \cdot 10^{-7}$ for BG. The maximum O concentration is observed a little later: 1.28 % at $\tau = 0.5 \cdot 10^{-5}$s in PG and 0.25 % at $\tau = 10^{-4}$s in BG, then the concentration decreases to 0.37 % at $\tau = 0.3$s in PG

and 1.2-10-5 % in BG. Thus, the time of nitrogen dioxide formation in BG is shorter than in PG, since this formation starts later, therefore, a smaller amount of nitrogen dioxide is obtained at the end of combustion.
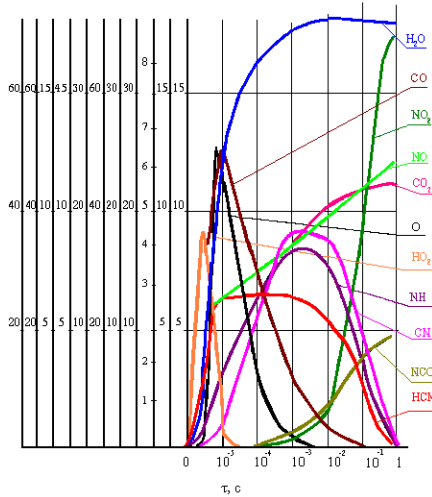

Fig. 2. Results of a computer calculation of the kinetics
of natural gas combustion

In contrast to nitrogen dioxide, the nature of nitrogen oxide formation is different for NG and BG. The similarity of the curves is maintained at the beginning of combustion, when "fast" nitrogen oxide is formed. This occurs for GHG at $\tau=0.5\text{-}10^{-5}$ s (increase to 1.25-10-^{2}%) and for BG at $\tau=10^{-4}$ s (increase to 7.21-10^{-3}%). At subsequent time points, the nitrogen oxide content for BG slightly increases and by $\tau=0.5$ s is 8.40-10^{-3}%. During the combustion of NG, a rather intense increase in the nitrogen oxide content continues, which by $\tau=0.3$ s is 2.4-10^2%. At the same time, there are differences for GHG and BG in the curves of HCN, NH, CN concentrations, which are more striking for GHG.
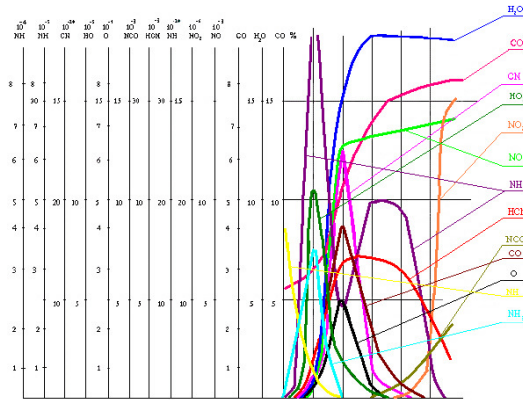
Fig. 3. Results of computer calculation of the kinetics of biogas combustion with an admixture of 0.004% NH_3

The formation of HCN and the increase in its concentration practically "repeats" the formation of nitrogen oxide by the "fast" mechanism. The maximum value of $1.27 \cdot 10^{-2}$% for GHG is achieved at $\tau=10^{-5}$ s, for BG - $7.2 \cdot 10^{-3}$% at $\tau=10^{-4}$ s, which coincides with the completion of the formation of "fast" nitric oxide. At the same time, a peak of CN was observed - $4.49 \cdot 10^{-6}$ % in PG and $2.49 \cdot 10^{-7}$ % in BG. Subsequently, the decrease in HCN and CN content for BG is more gradual than for GHG. For some time, the concentration of HCN almost does not change: at $\tau=10^{-3}$ s, the content of CN is $1.25 \cdot 10^{-2}$ % for PG and $7.16 \cdot 10^{-3}$ % for BG. By $\tau=0.3$ s, the HCN content for BG changes slightly to $3.66 \cdot 10^{-3}$ %, while for NG it decreases by an order of magnitude to $3.11 \cdot 10^{-3}$ %. The maximum value of NH is reached at $\tau=10^{-3}$ s and amounts to $3.75 \cdot 10^{-9}$ % in PG and $2.0 \cdot 10^{-9}$ % in BG, up to $\tau=10^{-2}$ s this value almost does not change, then it decreases by $\tau=0.3$ s to $1.18 \cdot 10^{-9}$ % in PG and $5.57 \cdot 10^{-10}$ % in BG. In the final stage, the concentration of NCO increases to 7.88-10-3 % for PG and $3.22 \cdot 10^{-3}$ % for BG by the time $\tau=0.3$ s.

Thus, it can be concluded that a shift in the time of nitrogen oxide turnover in BG without nitrogen-containing impurities leads to a twofold reduction in "fast" nitrogen oxides, while the total amount of NO is also reduced by almost half.

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Now let's consider the combustion of biogas with nitrogen-containing impurities, the presence of which is typical for biogas from agricultural biogas plants.

The results of calculating the kinetics of the biogas combustion process with an impurity of 0.004% NH_3 are shown in Fig. 3, and with an impurity of 0.0008% NO - in Fig. 4.

Comparison of the graphs for biogas without impurities and biogas with impurities shows that the pattern of changes in the concentrations of all components is preserved, but the amount of nitrogen oxides increases with the addition of NH_3 and NO to the gas. The increase in nitrogen oxide concentration occurs in the area of "fast" nitrogen oxide formation up to $\tau=10^{-4}$s. For biogas with an admixture of ammonia only at $\tau=10^{-4}$s, the nitrogen oxide content reaches 1.28-10^{-2}% and weakly increases to 1.40-10^{-2}% at $\tau=0.05$s, after which it does not change. Simultaneous admixture of NH_3 and NO leads to an increase in the nitric oxide content by an amount equal to the initial content, while maintaining the character of the curves.

The decomposition of NH_3 occurs in both cases in the same way. The lifetime of NH_3 is only 10^{-4}s. By this point, all ammonia is converted to the rapidly decaying radicals NH_2 and NH, whose maximums are observed at $\tau=10^{-5}$ s and are 3.6-10^{-4}% for NH_2 and 1.77-10^{-5}% for NH. At $\tau=10^{-4}$ s, NH_2 decomposes completely, and the NH content decreases to 9.16-10^{-10}%; then the NH change curve is identical to the corresponding curve for biogas without impurities. The decay time of ammonia and amine radicals is equal to the period of formation of "fast" nitric oxide, which confirms their participation in the increase of "fast" nitric oxide content. Thus, the introduction of ammonia directly into the combustion zone does not have a predominant effect on nitric oxide, but rather causes a slight increase in concentrations. Probably, the addition of NH_3 as a method of nitrogen oxide suppression is effective only in the flame zone.

The pattern of change in the nitrogen dioxide curves is maintained with a slight increase in concentrations to a level that does not exceed the values for natural gas.

It should be noted that the total amount of nitrogen oxides at the outlet of the combustion zone during biogas combustion is lower than for natural gas. A comparative picture of nitrogen oxides formation for natural gas, biogas and their mixture is shown in Fig. 5.

At the time point $\tau=0.3$ s, the content of nitrogen oxide for unadulterated biogas is 65% lower and nitrogen dioxide 50% lower than for natural gas. Biogas admixture to natural gas in the proportion of NG: NG=1:1 results in a 45% reduction in nitrogen oxide and 22% reduction in nitrogen dioxide. Even for biogas containing NH_3 admixtures, the yield of nitrogen oxides is lower than that of natural gas, by 41% NO and 15% NO_2. Accordingly, for biogas with NH_3 and NO impurities, this reduction is 36% of nitrogen oxide and 17.5% of nitrogen dioxide.

All the results above were obtained in the calculations of combustion of stoichiometric gas-air mixtures of gas and air, with an excess air coefficient $\alpha=1.0$. To verify the reliability of the chosen model, similar calculations were additionally carried out for biogas containing NH_3 and NO impurities at values of the excess air ratio from 1.0 to 1.4. Based on the results of the calculations, graphs of the dependence of the nitrogen oxides content at the outlet of the combustion zone at $\tau=0.5$ s were constructed (Fig. 5). The maximum value of NO content equal to $1.53 \cdot 10^{-2}$ % was obtained at $\alpha=1.0$ and then decreases to $8.31 \cdot 10^{-3}$ % with an increase in α to 1.4. The highest amount of NO_2 ($9.62 \cdot 10^{-5}$ %) occurs at $\alpha=1.1$, and then decreases and becomes equal to $2.61 \cdot 10^{-5}$ % at $\alpha=1.4$.

The type of graphs coincides with the data of other researchers [1-5], which confirms the reliability of the calculation results.

Thus, the addition of biogas to natural gas can be recommended as one of the ways to reduce the yield of nitrogen oxides during combustion.
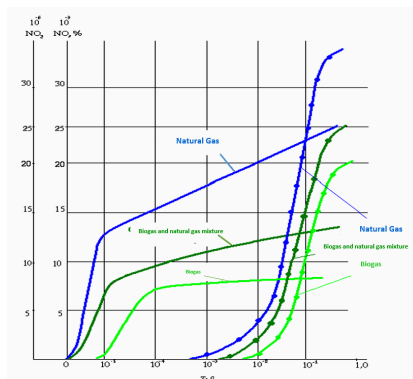

Fig. 4. Content of nitrogen oxides in the combustion products of natural gas, biogas and their mixture of NO and NO_2

Unfortunately, insufficient information on the kinetics of carcinogenic compounds (surfactants, N-nitrosamines) formation does not allow us to trace the nature of changes in the concentration of these components in the flame using the presented mathematical model. To determine their amount in the combustion products, field studies in thermal installations are required.
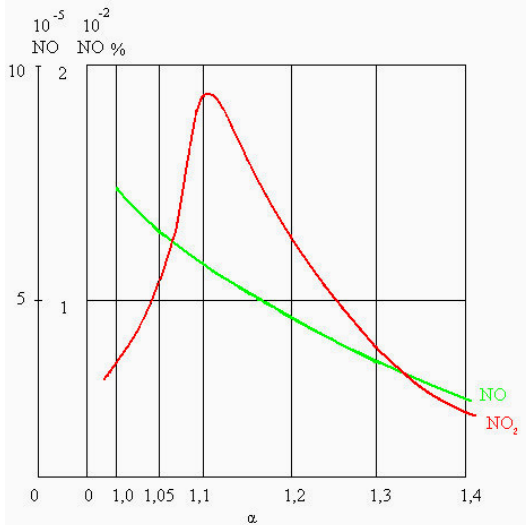

Fig. 5. Dependence of the nitrogen oxides content at the outlet of the combustion zone on the excess air ratio during the combustion of biogas containing NH_3 and NO impurities

Conclusions

The environmental characteristics of biogas, natural gas and their mixtures can be determined on the basis of the results of mathematical modelling of the dynamics of decomposition and formation of various components that affect the appearance of harmful substances.

The formation of harmful impurities in the combustion products of biogas, natural gas and their mixtures was studied using a mathematical model. According to computer calculations, it was found that the amount of carbon monoxide in biogas combustion is an order of magnitude less than in natural gas combustion products and amounts to $1,28 \cdot 10^{-2}$%.

The main harmful components in the combustion products of gaseous fuels are nitrogen oxides. Calculations have shown that the con-

tent of nitrogen oxides in biogas combustion products is 1.5-2 times lower than in natural gas combustion products due to the lower combustion temperature, the presence of CO_2 and H_2O in biogas. Adding biogas to natural gas in the proportion of BG: NG=1:1 results in a 45% reduction of NO and 22% reduction of NO_2. Even for biogas containing NH_3 and NO impurities, which is typical for biogas from agricultural BGUs, the yield of nitrogen oxides is lower than that of natural gas, by 36% NO and 17.5% NO_2.

Thus, the addition of biogas to natural gas can be recommended as one of the ways to reduce the yield of nitrogen oxides during the combustion of gaseous fuels is nitrogen oxide.

2. Determination of greenhouse gas emissions from the use of biomass.

The greenhouse gas emission rate for the energy use of biomass is determined by the emissions from fossil fuel combustion during the collection, processing and transportation of biomass. Given that biomass suitable for energy use in Ukraine refers to waste production, GHG emissions associated with harvesting and collection of biomass were not considered, as energy costs were fully attributed to the production of main products. In this case, the emission figure for biomass $e_{CO_2}^{BM}$ is composed of two components

$$e_{CO_2}^{BM} = e_{Transp}^{BM} + e_{proc}^{BM}, \qquad (2.1)$$

where e_{Transp}^{BM} - the greenhouse gas emission rate associated with biomass transport, gCO_2-eq/(kg tce of biomass);

e_{proc}^{BM} - the greenhouse gas emission rate associated with biomass processing and preparation, gCO_2 - eq/(kg tce of biomass).

Due to low bulk density of biomass of 100-150 kg/m^3, its transportation over long distances is not very efficient, therefore in calculations maximum transportation distance is assumed to be 100 km, and vehicles are used for transportation. Fuel costs for transportation of biomass Q_{VTr}^{BM} and greenhouse gas emission rate $e_{CO_2}^{NP}$ according to [8]

$$e_{Transp}^{BM} = e_{CO_2}^{VTr \cdot BM} = Q_{VTr}^{BM} \cdot e_{CO_2}^{NP}, \qquad (2.2)$$

and

$$Q_{VTr}^{BM} = 0.1 S_{Vtr}^{BM} \left[H_2 + H_W \cdot G_{BM} \right] = (1 + \textstyle\sum_i), \qquad (2.3)$$

Table 2.1

Specific energy consumption for biomass shredding [5]

Particle size, mm	>25	>15	>10	>5	>3
Specific energy consumption, $b_{ee}^{sherd \cdot BM}$, kWh/t	10-25	20-35	25-45	40-80	60-130

where Q_{VTr}^{BM} - fuel consumption for biomass transportation, l;

H_z - basic linear fuel consumption rate [138], l/100 km;

H_W - norm of fuel consumption for transport work, for petrol vehicle equals 2.0 l/t km, for diesel vehicle - 1.3 l/t km;

G_{BM} - mass of biomass transported by vehicle, t;

S_{Vtr}^{BM} - distance travelled, km;

K_i - coefficients taking into account additional fuel costs when transporting cargo within the city limits equal to 0.1-0.05;

$$e_{CO_2}^{pp} = e_{CO_2}^{VTr \cdot pp} + e_{CO_2}^{rTr \cdot pp} + e_{prod}^{pp} + e_{transp}^{pp} + e_{comb}^{pp} + e_{CO_2}^{combpp}, \quad (2.4)$$

where $e_{CO_2}^{PP}$ - emission factor for petroleum products (petrol, diesel fuel, fuel oil), gCO$_2$-eq/kg tce of petroleum product;

$e_{CO_2}^{VTr \cdot pp}$ - emission factor for transportation of oil products (gasoline, diesel fuel, fuel oil) in tank trucks, gCO$_2$-eq/kg t of oil product;

$e_{CO_2}^{rTr \cdot pp}$ emission rate during transportation of petroleum products by rail, gCO$_2$-eq/kg tce of petroleum product;

$e_{prod}^{pp} + e_{transp}^{pp} + e_{comb}^{pp}$ - emission factor for refining, transportation and extraction of oil, respectively, gCO$_2$-eq/kg tce of oil product;

$+ e_{CO_2}^{combpp}$ - emission factor during petroleum product combustion, gCO$_2$-eq/kg tce of petroleum product.

In the calculations, the volume of the truck body was varied from 8 m^3 (MAZ-53) to 52 m^3 (KAMAZ-54 specialized truck for grain transportation) [3, 4].

Processes for the preparation of biomass, as an energy fuel, include two alternative processes: shredding and pressing (briquetting).

Consequently, the total greenhouse gas emissions for biomass preparation and processing are as follows

$$e_{prod}^{BM} = e_{CO_2}^{prezBM} + e_{CO_2}^{shred \cdot BM} \ . \tag{2.5}$$

The energy consumption for shredding depends on the final biomass particle size (Table 2.1 [145]) and the type of biomass. The maximum energy input refers to the shredding of woody biomass, the minimum to straw.

Accordingly, the greenhouse gas emissions associated with biomass $e_{CO_2}^{sherd \cdot BM}$ shredding were determined using the relationship

$$e_{CO_2}^{shwrd \cdot BM} = b_{ee}^{shwrd \cdot BM} \cdot E_{ee}. \tag{2.6}$$

Biomass baling and pelletising can be carried out using several well-known processes, the names of which determine the type of equipment used (Figure 2.2 [6]). Electricity consumption directly for biomass pressing is 20-70 kWh/t (Table 2.2 [6, 7]).

Table 2.2

Energy consumption for briquetting and pelletizing of biomass

Type of equipment used	Rolling press	Screw press
Electricity costs, $b_{ee}^{press.BM}$, kWh/t	20-60	50- 0

In addition to energy costs, biomass baling technology involves drying the biomass to a predetermined moisture content. In this case,
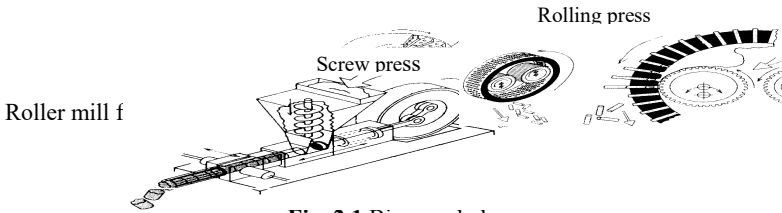

Fig. 2.1 Biomass bal

the thermal energy consumption is $b_{Tem}^{hress \cdot BM} = 0{,}02 - 0{,}08$ Gcal/(t biomass) [7].

Accordingly, the greenhouse gas emissions from biomass $e_{CO_2}^{press \cdot BM}$ baling include emissions associated with both heat and electricity use

$$e_{CO_2}^{press \cdot BM} = EMBEDEquation.3\Theta E_{\text{вв}} + b_{Tem}^{press \cdot BM} E_{Tem} . \qquad (2.7)$$

The above methodology made it possible to estimate greenhouse gas emission values for various fossil fuels and biomass, on the basis of which various options of technologies and equipment for biomass energy use were compared.

2.1 Study of greenhouse gas emissions in energy production in Ukraine

2.1.1 Study of greenhouse gas emissions during the use of fossil fuels.

The methodology described above and the calculation of greenhouse gas emission rates were not meant to make an inventory of greenhouse gas emissions in the Ukraine, but to obtain quantitative data enabling evaluation of the efficiency of fossil fuels replacement with biomass. In this regard, the range of variation of emission indicators was calculated, both for main fossil fuels and biomass waste. Attention was also paid to studying the structure of the components of greenhouse gas emission indicators.

The values of greenhouse gas emission indicators for the main types of fossil fuels in European countries, California and Ukraine are shown in figure 2.5 and table 2.5.
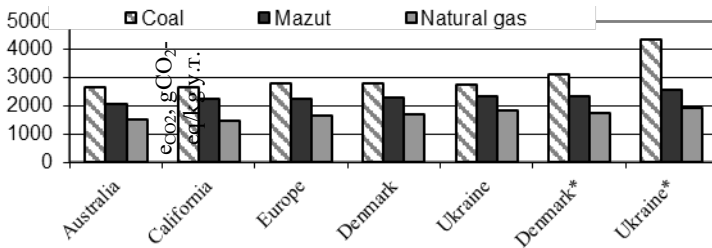

Fig. 2.2. Fossil fuel greenhouse gas emission rates

The emission values in Fig. 2.5 for Australia (148), California (149), Europe (150), Denmark (151) and Ukraine are given for the combustion stage only. Values for Denmark* (152) and Ukraine* include energy inputs for the whole fuel production cycle. Thus, we can say that emissions related to fossil fuel combustion for different countries are almost the same. The marginal deviation of emission figures does not exceed 5%. The main difference in fossil fuel emis-

sions is due to the indirect greenhouse gas emission component in the upstream and downstream stages. Comparison of this component for Ukraine and Denmark shows that indirect greenhouse gas emissions at coal use in Ukraine are 2-5 times higher.

Analysis of the structure of the indirect component of greenhouse gas emissions for coal (table 2.3 and fig. 2.3) shows, that the share of coal mine methane emission constitutes from 47% to 96% of the total emissions. At the same time the emission value associated with heat and electric energy consumption during coal extraction may vary by tens of times. The main share of emissions is attributable to carbon dioxide CO_2 (Fig. 2.4).

Table 2.3

Greenhouse gas emission values for the main fossil fuels in Ukraine

	Type fluel	Coal		Petrol		Mazut		Diesel fuel		Natural gas	
		gCO$_2$/ kg у.т.	%	gCO$_2$/kg у.т.	%	gCO$_2$/kg у.т.		gCO$_2$/kg у.т.	%	gCO$_2$/kg у.т.	%
max	$e_{CO_2}^{prod}$	1531	35.2	1,9	0,1	1,9	0,1	1,9	0,1	-	-
	$e_{CO_2}^{transp}$	34	0.8.	2,0	0,1	2,1	0,1	2,0	0,1	95,7	5,0
	$e_{CO_2}^{proc}$	-	-	150,5	6,5	143,4	5,6	152	6,2	-	-
	$e_{CO_2}^{tr}$	-	-	63,0	2,7	19,0	0,7	64,1	2,5	-	-
	$e_{CO_2}^{comb}$	2785	65.0	2117	90,6	2375	93,2	2225	91,0	1812	95,0
	e_{CO_2}	4350	100	2334	100	2555	100	2446	100	1908	100
min	$e_{CO_2}^{prod}$	763	22,7	1,4	0,1	1,4	0,1	1,4	0,1	-	-
	$e_{CO_2}^{transp}$	-	-	0,1	0,0	0,1	0,0	0,1	0,0	73,1	4,3
	$e_{CO_2}^{proc}$	-	-	77,6	3,5	75,8	3,1	78,8	3,4	-	-
	$e_{CO_2}^{tr}$	-	-	1,0	0,0	-	-	1,0	0,0	-	-
	$e_{CO_2}^{comb}$	2601	77,3	2117	96,4	2330	96,7	2225	96,5	1641	95,7
	e_{CO_2}	3364	100	2197	100	2501	100	2685	100	1714	00

It is 81% for coal, 99% for fuel oil and 96% for natural gas, respectively. At the same time, the total N2O component does not exceed 4 percent for all fossil fuels, and the methane share for fuel oil and natural gas does not exceed 0.5 percent. Hence, the lack of relia-

ble data on N2O and CH4 emissions cannot lead to significant inaccuracies in the emission factor calculations for fossil fuels.
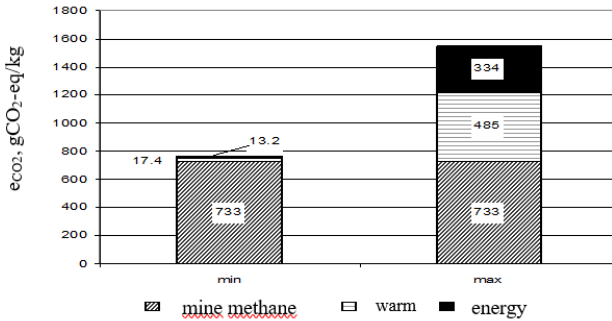

Fig. 2.3. Structure of the indirect component of greenhouse gas emissions

A similar conclusion can be drawn for emissions caused by the consumption of fuel during transport. This is primarily true for coal and fuel oil transport (Fig. 2.3).

2.1.2 Research into greenhouse gas emission while using biomass

The greenhouse gas emission indicator for biomass is associated with the technology of its preparation for combustion. The main preparation stages are: transportation, shredding, briquetting (pelletizing) or various combinations of these stages. The calculations were applied to waste biomass with bulk density 100-150 kg/m^3, which includes sunflower husk, rice and buckwheat husk, and sawdust. Thus, the maximum value of the indicator of greenhouse gas emission in consideration of transportation, shredding and the following granulation is 125.2 gCO_2-eq/kg t, and the minimum value, supposing just the transportation on 10 km by the specialized transport, is 0.8 gCO_2-eq/kg t. The part of carbon dioxide in the total emission is from 95% to 98%.
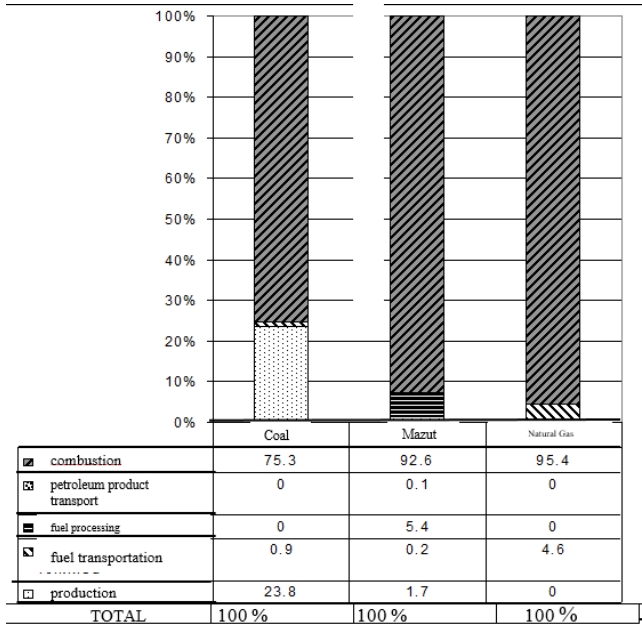
Fig. 2.4. Ratio of greenhouse gas emission components
for different fossil fuels

2.2 Investigation of the environmental efficiency of various technologies and equipment for biomass energy use

Analysis of dependence of specific GHG emission reduction value (2.1) shows that it is determined by three values: ratio of emission indicators and efficiency of energy units, as well as absolute value of fossil fuel emission indicator.

Based on data (Tables 2.3 and 2.4) on emission figures, the ratio $e_{CO_2}^{BM}/e_{CO_2}^{ff}$ varies between 0.00018 and 0.073. For each fossil fuel, the value of the ratio is given in Table 2.4.

Given that the ratio of efficiencies in dependency (2.4) is not significantly different from unity, it can be argued that the biomass GHG emission value can change the final result by 3-8%.

Table 2.4

Value ratios of biomass emission rates and fossil fuels, $e_{CO_2}^{BM}\big/e_{CO_2}^{ff}$

Type of fuel to be replaced	coal	Mazut	Natural gas
Maximum value	0,037	0,050	0,073
Minimum value	0,00018	0,00031	0,00042

Based on the efficiency values of hot water boilers burning fossil fuels and biomass (Table 1.1, Chapter 1), it follows that the ratio $\eta_{\Sigma BM}\big/\eta_{\Sigma ff}$ can vary from 1.34 to 0.753 (Table 2.5). In other words, the efficiency of energy units significantly affects the result of replacing fossil fuels with biomass.

The range of possible changes in specific GHG emission reduction in case fossil fuels are replaced by biomass using direct combustion technology for thermal energy generation is shown in Fig. 2.5.

Table 2.5

Efficiency ratios for hot-water boilers fired by biomass and fossil fuels on biomass and fossil fuels $\eta_{\Sigma BM}\big/\eta_{\Sigma ff}$

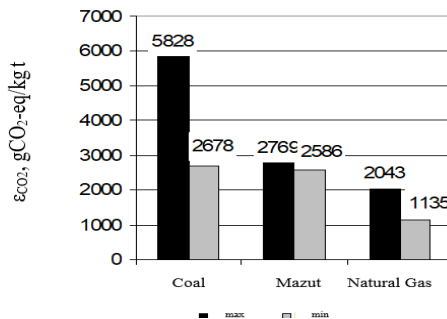| Boiler heat output	Value	Replaceable fuel		
		Coal	Mazut	Natural gas
Up to 100 kW	max	1,169	–	1,071
	min	0,833	–	0,76
From 100 kW to 10 MW	max	1.34	1,084	1,059
	min	0,854	0,753	0,735

Fig 2.5. Specific reduction of greenhouse gas emissions εCO_2 when replacing fossil fuels with biomass in heat production

An analysis of co-combustion of fossil fuels and biomass is of interest. When fossil fuels are partially replaced by biomass, the emission rate for the mixture of fuels decreases proportionally to the share of biomass (Fig. 2.6). With direct combustion of biomass, the substitution with coal is most likely and most efficient. In this case, the efficiency of the boiler and the whole plant changes as well. This is connected, first of all, with the change of heat losses with flue gases (q_2) and bottom ash (q_6).
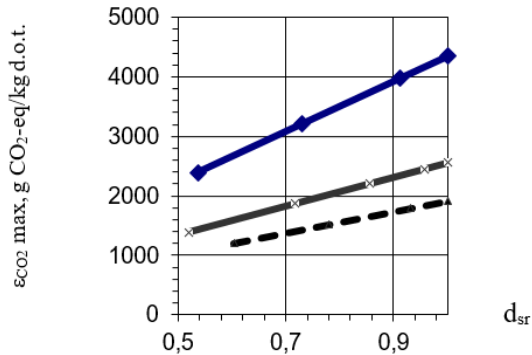

Fig. 2.6. Emission value εCO_2 as a function of energy fraction d of fossil fuel co-combustion with biomass: *1* - coal + biomass; *2* - fuel oil + biomass; *3* - natural gas + biomass

In modelling the boiler operation with partial replacement of coal by biomass, exactly these factors were taken into account. The calculation results showed that the change in boiler efficiency does not exceed 1% (tab. 2.6). Real experience of combined combustion of coal and biomass confirms the obtained results of insignificant change of boiler efficiency [6-8].

Table 2.6

Boiler operation indicators at partial substitution of coal for biomass

Boiler heat output	Value	Replaceable fuel		
		Coal		
Up to 100 kW	max	1,169	–	1,071
	min	0,833	–	0,76
From 100 kW to 10 MW	max	1.34	1,084	1,059
	min	0,854	0,753	0,735
Mass fraction of coal in the fuel mix-	0,7	0,8	0,9	1

ture				
Boiler efficiency,%	88,9	89,2	89,4	89,6
$\eta_\Sigma^{CM}/\eta_\Sigma^{HCK}$	0,992	0,995	0,998	1
ε_{co2} max g CO_2-eq/kg o.t	3208,6	3594,7	3980,1	–

Gasification and pyrolysis are additional thermal processing steps and therefore reduce the overall efficiency of the biomass energy use process.

When using both chemical and physical energy from the generator gas, e.g. by burning it in boilers, gasification efficiencies range from 60% to 90%. The maximum values apply to medium power plants and the minimum values to low power plants. At use of generator gas in engines and turbines additional losses are connected with necessity of cooling of generator gas for the purpose of its cleaning [7].

Thus, at production of thermal energy the efficiency of boiler units, using direct combustion of biomass, is higher, on average, by 5-10 %, than at use of gasification. This is clearly seen in the presented data in table 2.7.

Table 2.7

Overall efficiency of district heating system in the gasifier+boiler scheme, %

Gasification efficiency, %	Boiler efficiency 85%	Boiler efficiency 90%	Boiler efficiency 95%
70	59,5	63,0	66,5
80	68,0	72,0	76,0
90	76,5	81,0	85,5

A similar reduction in overall efficiency applies to pyrolysis processes. For example, the efficiency of liquid fuel production by fast pyrolysis using the RTPtm process is, according to real data, 85%. Naturally, this reduces the overall efficiency of energy production by 12-14%.

The analysis of the proposed pyrolysis technology in the hot air flow showed that the process efficiency is determined by the loss of physical heat of hot coke residue removed from the system. As the

pyrolysis gas is used in hot state without cooling. Taking into account that residue mass is 30-40% of the original fuel, and its heat capacity is 1,01 kJ/(kg-K) , portion of losses from heat of biomass combustion is 8-10 % at residue discharge temperature 500-700 ºC. Therefore, the pyrolysis efficiency would be 90-92 %.

Taking into account the obtained efficiencies of biomass gasification and pyrolysis energy production processes, the limit values of specific greenhouse gas emission reduction indicator ε_{CO_2} , presented in fig. 2.7, are determined.

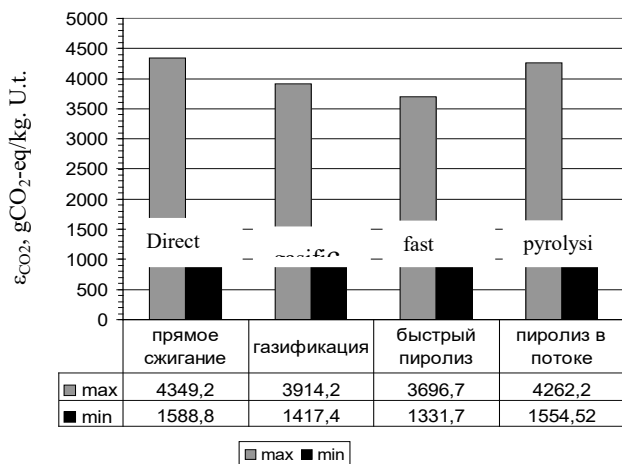|	прямое сжигание	газификация	быстрый пиролиз	пиролиз в потоке
max	4349,2	3914,2	3696,7	4262,2
min	1588,8	1417,4	1331,7	1554,52

Fig. 2.7. Values of specific greenhouse gas emission reductions εCO$_2$

It follows that the most efficient technologies for the energy use of biomass are direct combustion technologies. Pyrolysis technology in a hot air stream is close to them and is competitive in terms of environmental efficiency. All of the above shows the relevance of the development of pyrolysis technology and further research in this field.

General 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 indicator of specific greenhouse gas emission reduction. This indicator allows for an ob-

jective comparison of existing and proposed technologies and equipment for the use of bioenergy fuels, while fully taking into account the complex effect 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 kCO_2 for the conditions of Ukraine were determined, which were: for petrol - $2188 \div 2329$ gCO_2-eq/kg d.o.w., fuel oil - $2414 \div 2552$ gCO_2-eq/kg d.o.w, natural gas - $1712 \div 1910$ gCO_2-eq/kg d.o.w. and combustion of biogas produced by anaerobic digestion of biomass - $1037 \div 1253$ gCO_2-eq/kg d.o.w. Based on the studies performed, the ranges of possible specific reduction of greenhouse gas emissions when replacing natural gas with bioenergy fuel produced by anaerobic digestion of biomass were determined.

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