ENERGY AND ENVIRONMENTAL ANALYSIS OF BIOENERGY TECHNOLOGIES

UABio Position Paper N 8

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Introduction

Position Paper N 8 prepared by the Bioenergy Association of Ukraine covers the issue of energy efficiency of different bioenergy technologies. The Paper also includes assessment of GHG balance when replacing fossil fuels by biomass.

Justification of the importance of energy and environmental analysis of bioenergy technologies

Ukraine as a member of the Energy Community (from 2011) is obligated to implement a number of European directives. In the course of further signing of the sections of Ukraine-EU association Agreement Ukraine will have more and more obligations including ones in the energy sector.

One of the main EU's documents in the renewable energy sector is Directive 2009/28/EC [1], which was to be implemented by Ukraine by 1 January 2014 within Ukraine's Energy Community commitments [2]. An important provision of the Directive is the requirement to reduce greenhouse gases emissions by the implementation of bioenergy technologies by at least 35% compared to the use of fossil fuels. At that from 1 January 2017 this minimum requirement increases to 50% and from 1 January 2018 to 60% for the installations put into operation from 01.01.2017.

Another important aspect of possibility and feasibility of implementation of bioenergy technologies is their energy efficiency. This efficiency is determined through comparison of the amount of energy generated by a bioenergy installation and energy spent for manufacturing and providing operation of the installation. Currently, there are no binding requirements on the energy efficiency of bioenergy technologies in the EU and in the world, but some guidelines have been developed in the framework of Task 32 of the International Energy Agency [3]. These recommendations seem to be desirable for practical application in Europe and in Ukraine.

Energy efficiency indicator is important because it provides an unbiased estimate of a certain bioenergy technology. This estimate does not depend on the current state policy regarding this technology, which can be aimed to stimulate or hold back its development through, for example, feed-in tariffs, subsidies, tax incentives and other mechanisms.

Authors of the study [3] suggested an *energy yield coefficient* (EYC_{NR}) for estimation and comparison of renewable energy technologies. The coefficient is a ratio of the cumulative energy production by an installation (output energy) to the cumulative demand of non-renewable energy (fossil fuels) required for manufacturing, providing operation of the installation during its lifetime and its disposal afterwards (non-renewable input energy).

The feature of EYC_{NR} is that input energy includes only non-renewable energy, thus RES like biomass are not included in it. Evidently that under such approach the energy yield coefficient for RE plants must be >1 and for fossil fuel plants it is always <1. According to recommendations of the study [3], sufficiently high energy efficiency of a RE technology corresponds to EYC_{NR} that is at least > **2**, and the most desirable range is > **5**.

It should be mentioned that besides the energy yield coefficient one can also find other energy efficiency factors in literature. In fact they all use input energy and output energy categories, the difference between them and EYC_{NR} lies in the way of their comparison. The authors of this Position Paper consider EYC_{NR} to be the most convenient indicator and it is used it in the paper.

Estimation of energy efficiency of processes and calculation of GHGs balance are components of a Life Cycle Assessment [4]. LCA is a comprehensive analysis of the environmental impact caused by the introduction and use of a certain technology. It should be noted that the full Life Cycle Assessment includes determining a rather wide range of parameters, but the most significant are energy balance and greenhouse gases balance. These very indicators are analyzed in the Position Paper.

This approach is consistent with results of the study [5], in which the authors have analyzed nearly 100 papers on LCA of bioenergy technologies performed during last 15 years for conditions of different parts of the world, including Europe. The studies covered technologies for heat, power and biofuels production from various types of biomass; most of them were connected with bioethanol and biodiesel production (**Figure 1**). Study [5] shows that half of all the above papers involves only an estimation of energy balance and/or balance of greenhouse gases; the other half represent the full Life Cycle Assessment of bioenergy technologies (**Figure 2**).

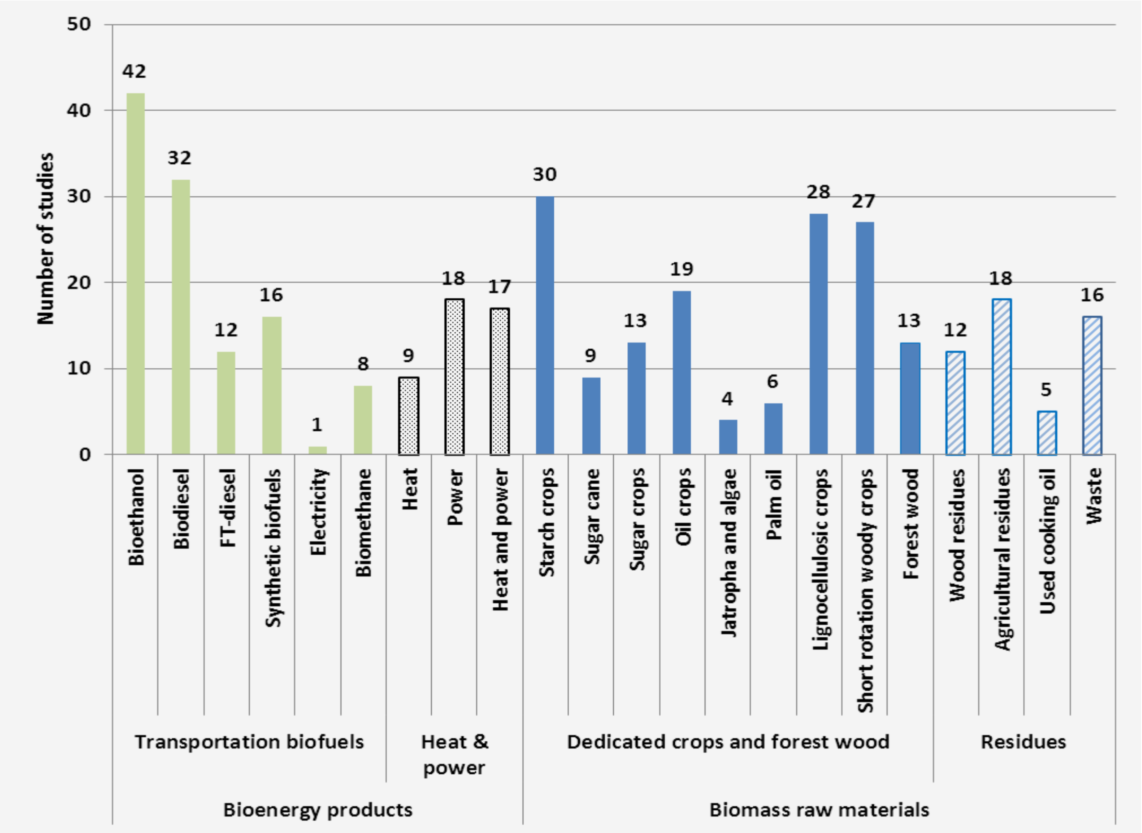


Fig. 1. Type of bioenergy products and biomass raw materials covered by the reviewed studies [5]

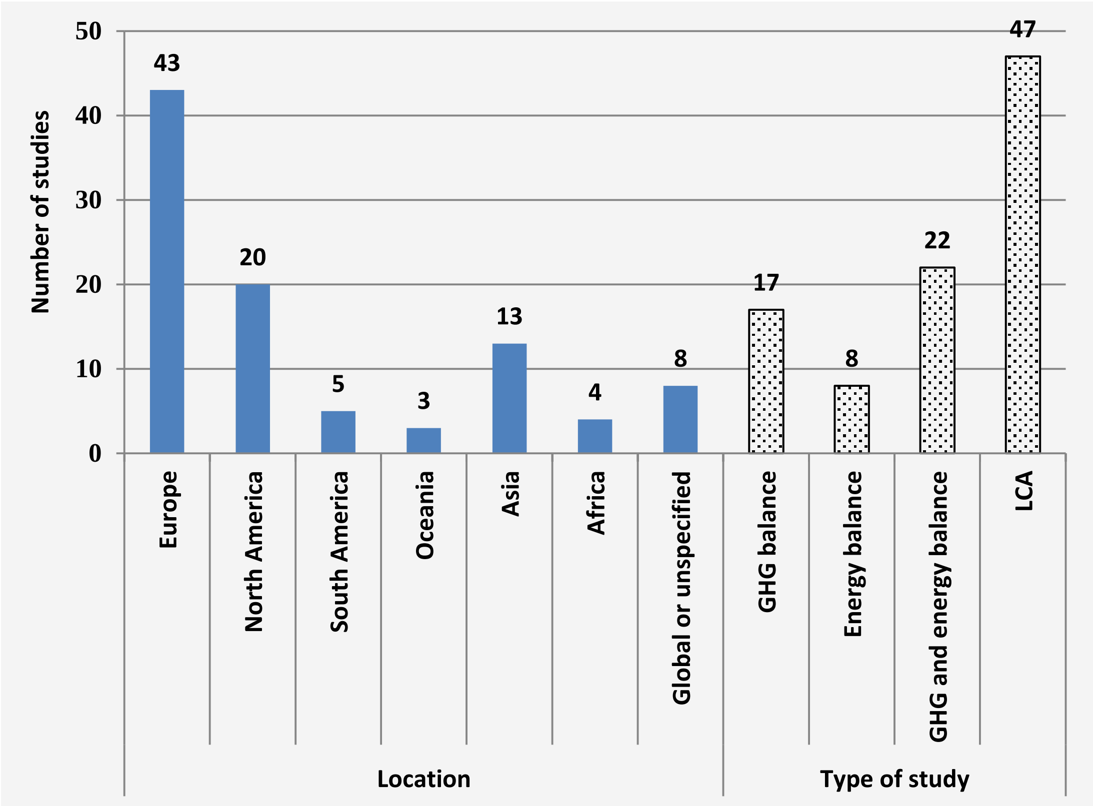


Fig. 2. Location and type of study [5]

Energy analysis

In this chapter, results of the available studies including results obtained by the authors of the Position Paper for Ukraine [6, 7] are presented. All the studies deal with energy analysis of bioenergy technologies with the use of energy yield coefficient EYC_{NR} (**Table 1**). For comparison, the table also includes EYC_{NR} values for some fossil fuels energy installations. It should be noted that one can compare results of the different investigations only at large as details of many studies (such as capacity and efficiency of the installations, biomass transportation distance etc.) are not available.

These data show that all the energy plants on solid biomass (wood, straw) designed for heat production and combined heat and power production have energy yield coefficient $\boldsymbol{EYC_{NR}} > \mathbf{2}$ (i.e. more than the minimum required value), and some of them have $\boldsymbol{EYC_{NR}} > \mathbf{5}$ that corresponds to the most recommended range. The concrete value of the coefficient depends on a combination of many factors (type of biomass/biofuels, capacity and efficiency of an energy installation, the distance and means of transporting biomass etc.). Biomass TPPs have the worst performance: $\boldsymbol{EYC_{NR}} < \mathbf{5}$ or even $< \mathbf{2}$ depending on the type of biomass and other conditions. This means that generation of electricity alone is less energy efficient than production of heat or combined heat and power production from biomass.

Table 1. Energy yield coefficient for different energy installations[1)]

Type of energy plant	EYC_{NR}
Wood biomass plants	
Log wood boiler [3]	**4.2-12.1**
Boiler for wood residues (150 kW) [16]	**8.3**
Boiler for wood chips [3]	**4.8-12.1**
Boiler for wood chips (500 kW) (Ukraine)[2)]	**6.8**
Boiler for energy willow chips (300 kW) (Ukraine)[2)]	**6.1**
Boiler for wood pellets (100 kW) (Ukraine)[2)]	**2.4**
Small DH system based on wood [3]	**4.0**
Large DH system based on wood [3]	**4.2**
Large DH system based on wood with peak-load oil fired boiler [3]	**2.2**
Boiler for wood pellets with additional solar energy collector [3]	**3.3**
Biomass DH system with solar energy collector [3]	**4.0**
CHP plant running on wood chips (2 MW_{el}+10 MW_{th}) (Ukraine)[2)]	**7.1**
Thermal power plant running on wood chips (2 MW_{el}) (Ukraine)[2)]	**1.7**
Thermal power plant running on wood residues (30 MW_{el}) [16]	**4**
TPP (500 MW_{el}): co-combustion of wood residues (5% mass) and coal [16]	**2.2**
Straw plants (Ukraine)[2)]	
Boiler for bailed straw (500 kW)	**8.0**
Boiler for straw pellets (100 kW)	**3.6**
Large DH system based on straw with peak-load oil fired boiler (Europe) [3]	**1.8**
CHP plant running on bailed straw (2 MW_{el} + 10 MW_{th})	**5.4**
Thermal power plant running on bailed straw (2 MBm_{el})	**1.3**
Thermal power plant running on bailed straw (25 MW_{el}) (Spain) [19]	**2.1**[7)]
Biogas plants	
Biogas produced from chicken manure [15]	**1.8-1.9**
Biogas from manure [20]	**2.6-3.0**[3)]
Biogas from energy crops [20]	**2.4**[3)]
Biogas produced from maize silage [14]	**1.8-2.2**
Biogas from grease sludge	**6.2**[3)]
Installations for motor fuels production	
Biodiesel[6)] (RME) and by-products [3]	**2.4**
Biodiesel (RME) and by-products [18]	**2.6**
Biodiesel (RME) [3]	**1.5-4.0**
Biodiesel (RME) [18]	**1.9**
Biodiesel (RME)(Ukraine) [9]	**1.36-1.7**[3)]
Biodiesel from soybean (USA) [18]	**3.21**
Bioethanol from sugar beet [3]	**2.1**
Bioethanol з sugar beet [8]	**1.0-1.59**[3)5)]
Bioethanol from wheat [8]	**2.23**[3)5)]
Bioethanol from wheat [17]	**1.93**[3)5)]

Bioethanol (ETBE) wheat and sugar beet [17]	**0.9-1.05**[3)5)]
Bioethanol from wheat, barley, maize, sugar beet (Ukraine) [9]	**0.8-1.1**[3)]
Bioethanol from maize (USA) *[10-12]*	**0.59-1.25**[3)]
Other renewable energy plants [3]	
Solar heating	**4.0**
Fossil fuel plants [3]	
Light fuel oil boiler with flue gas condensation	**0.7-0.76**
Light fuel oil boiler	**0.67-0.72**
Light fuel oil heating	**0.66**
Natural gas boiler with flue gas condensation	**0.74-0.81**
Natural gas boiler	**0.7-0.74**
Natural gas boiler with additional solar energy collector	**0.85**
Large DH system based on geothermal energy and natural gas	**1.18**
Oil boiler with additional solar energy collector	**0.75**
Heat pump with collector in the soil	**1.04**
Heat pump with probe in the soil	**0.99**

1) For the conditions of Europa unless other is indicated.
2) Results obtained by the authors of the Position Paper (biomass transportation distance is 50 km).
3) The value is calculated by the authors of the Position Paper on the basis of the respective study data.
4) Biomass/biofuels transportation distance.
5) Allocation of energy demand by mass of final products.
6) Hereafter in the table: biodiesel from rapeseed unless other is indicated.
7) For the cereals yield of about 7 odt/ha. Under a lower yield EYC_{NR} <2.

As for biodiesel and bioethanol production, the situation is ambiguous. According to some sources, the energy yield coefficient for them is > 2; according to some others it is much lower. It appears that the result strongly depends on the feedstock, the applied technology and other conditions. This issue will be discussed in more detail below.

Energy efficiency of biogas plants strongly depends on a feedstock type and other conditions. This issue requires additional research and may be the subject of one of next Position Papers by Bioenergy Association of Ukraine.

All energy plants using fossil fuels have $EYC_{NR} < 1$ (as it must be), except for the case of combined use of fossil fuels and renewables.

Heat production from biomass

As shown above, all the boilers designed for the production of energy from biomass have high energy efficiency. Therefore, comparison of direct combustion with other biomass thermochemical conversion technologies is of interest. Such comparison was done in [13], where the authors studied energy efficiency of solid biomass (wood chips) boilers and biomass gasifiers (the gasification was followed by combustion of producer gas in a boiler).

The authors considered three types of biomass – forest residues, miscanthus, poplar from short rotation coppice, and three types of gasification – O_2-blown pressurized entrained flow, O_2-blown pressurized circulating fluidized bed and air/steam-blown indirect atmospheric gasification. The reference system was a gas boiler. For all the studied technologies the energy yield coefficient was calculated.

The obtained results show that direct combustion, entrained flow gasification and gasification in CFB have quite high, close to each other energy efficiency indicators: EYC_{NR} = 5.5-8 (**Fig. 3**). For the air-steam indirect gasification the energy yield coefficient is even higher: 9-11. If we compare different types of biomass, we see that for all the considered technologies the highest EYC_{NR} is for miscanthus, and forest residues occupy the second place. For the gas boiler (the reference system) EYC_{NR} = 0.73 that fully coincides with the values given earlier in **Table 1**.

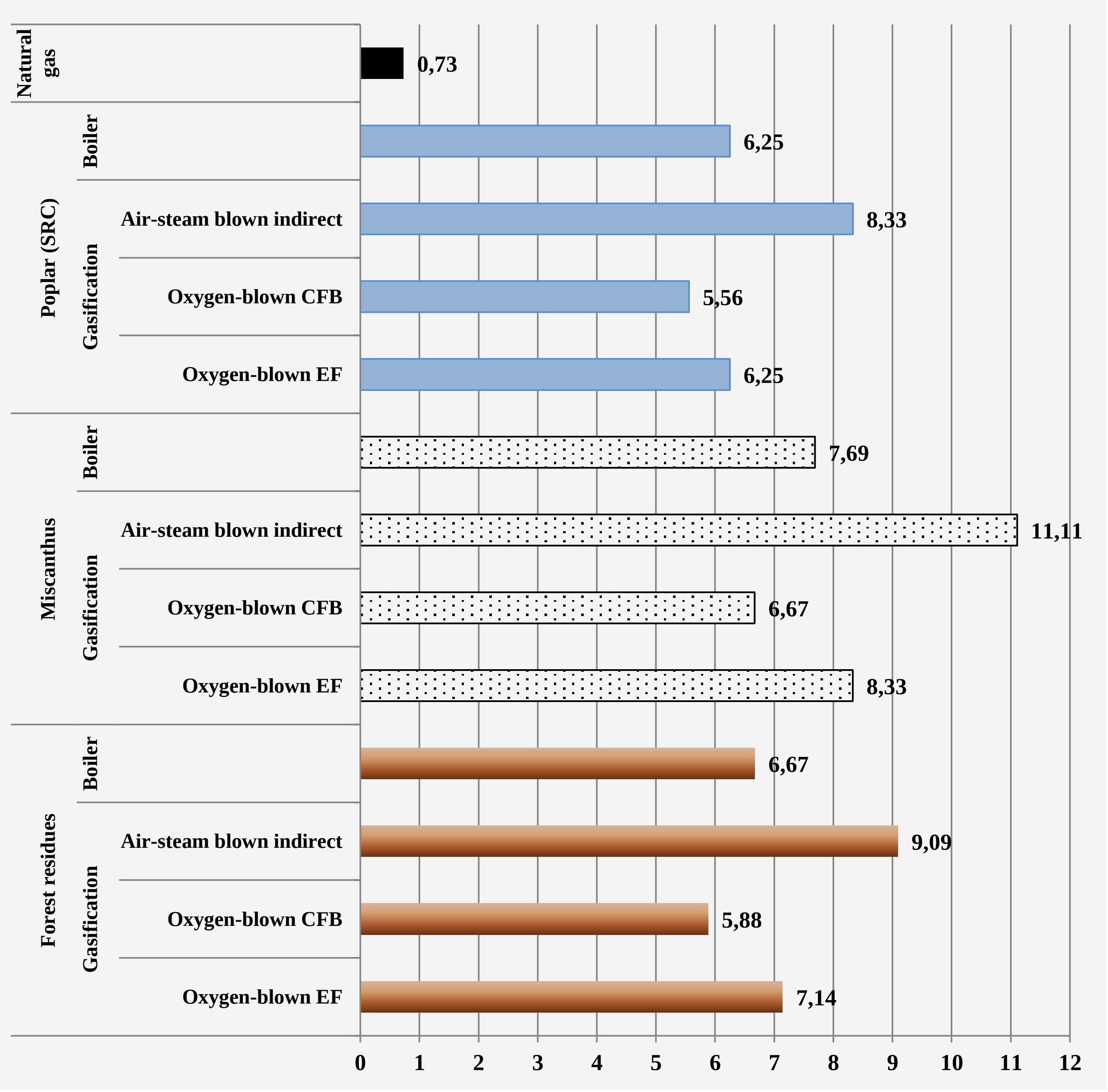


Fig. 3. Energy yield coefficient EYC_{NR} for direct combustion and gasification of biomass [13]

Power production from biomass

Energy efficiency and balance of greenhouse gases for power production from straw were studied in detail in [19] for Spain. An example of a 25 MW_{el} TPP running on straw bales of winter cereals (rye, triticale, oats) was investigated. In this case, it is considered that these crops are grown as dedicated energy crops.

It was established that the yield of the crops (3-11 odt/ha) had a large impact on the energy and environmental performance of the power station. This is because the consumption fuel required to perform a number of operations on biomass collection (e.g., mowing, baling) depends on a crop yield on respective land. Thus, for the two sites studied in [19], the consumption of diesel fuel for cutting plants ranged within 12.2-18.4 l/ha and 11.6-18.6 l/ha, and for baling within 7.8-10.6 l/ha and 9.2-14.9 l/ha respectively.

Consumption of fossil fuels for collecting and preparing biomass is an important part of the input energy and therefore affects the energy yield coefficient EYC_{NR}. This is especially important for power production from biomass as efficiency of these technologies is relatively low and it is necessary to know the most influencing factors. According to [19] the share of used diesel fuel for agricultural operations is 25-30% of the total input energy of the TPP.

The authors of the study [19] established that within the studied range of crop yield, the energy yield coefficient EYC_{NR} for the 25 MW_{el} thermal power plant ranged from 1.1 to 3.5 (**Fig. 4**). It means that depending on the energy consumption needed for collection and pretreatment of biomass, the TPP operation can be quite effective in terms of energy balance (EYC_{NR}> 2) or energy-inefficient (EYC_{NR} <2). The line corresponds to the crop yield of about 7 odt/ha.

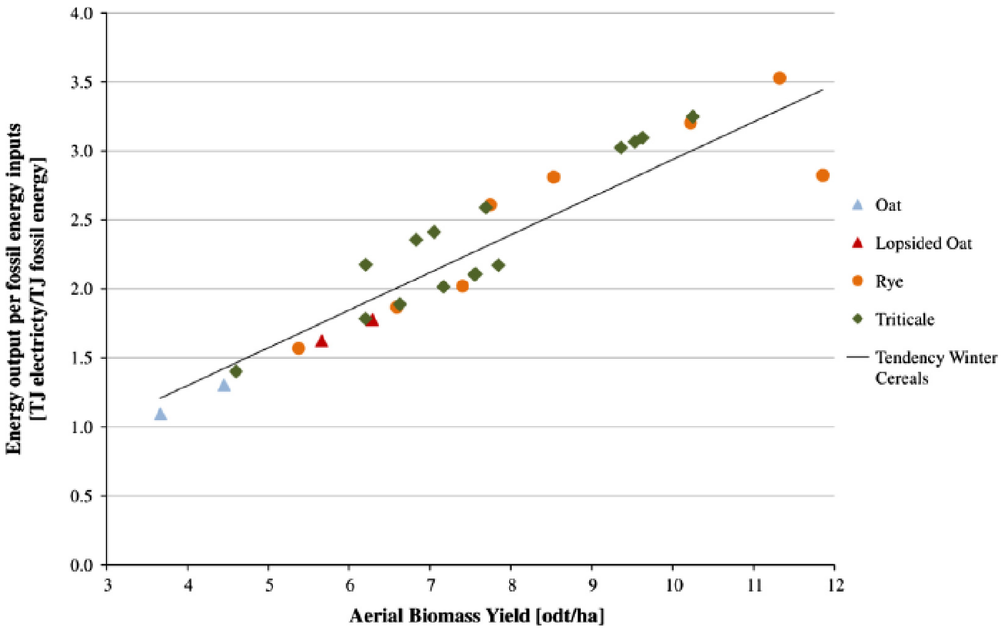


Fig. 4. Energy yield coefficient for 25 MW_{el} straw fired TPP depending on the cereals yield [19]

Production of biogas

Life cycle assessment of biogas technologies was carried out in the study [14] for Germany. The authors considered obtaining biogas from maize followed by electricity generation by a 255 kW_{el} engine. For the three administrative districts of Lower Saxony the authors analyzed the influence of local conditions, especially soil quality, climatic conditions, the applied cultivation technology and, therefore, the yield of maize, on energy and environmental performance of the biogas plants. Another important factor that influenced the results of the study was the share of used heat, which was considered a by-product of the biogas CHP unit.

The assessment showed that energy efficiency of the studied biogas CHP units was on the verge of the acceptable values. For the considered options, the energy yield coefficient EYC_{NR} was around **2** (the lowest recommended value for the bioenergy technologies) (**Table 2**). The highest value (**2.2**) was obtained for the biogas plant in Göttingen where consumption of fossil energy for cultivating maize was minimal and the share of used heat was the highest.

Table 2. Characteristics of the studied biogas technologies [14]

Indicator	Option I (Göttingen)	Option II (Celle)	Option III (Hildesheim)
Demand of fossil energy for cultivating maize, kgoe/t maize*	5.8	8.2	6.2
Power consumption by the biogas CHP plant, % produced power	7%	7%	7%
Heat consumption by the biogas CHP plant, kWh/m^3 biogas	0.256	0.256	0.256
Share of used heat	60%	30%	40%
EYC_{NR}*	**2.2**	**1.84**	**2.1**

** The values are calculated by the authors of the Position Paper on the basis of data [14].*

For biogas plants that use maize as feedstock, it is established that most part of fossil input energy (up to 70%) is spent on maize cultivation. Certain part of the fossil energy is consumed for transporting biomass to storehouses for silage and feeding it into bioreactor (an average biomass transportation distance assumed in the study was 20 km). Own energy needs of the biogas plants (power for stirring devices, pumps etc. and thermal energy for heating bioreactors) are completely covered at the expense of the produced biogas (up to 15-20%). The information may be useful to optimize input energy for a biogas plant and reach higher energy yield coefficient.

One can expect $EYC_{NR} > 2$ for the biogas plants which use a big share of agricultural waste or other kind of waste as feedstock. The conclusion is confirmed by results of [20] where the authors studied energy efficiency of Swedish biogas plants using different types of feedstock. The best result (**EYC_{NR} = 6.2**) was obtained for biogas production from grease sludge (**Table 3**). The feedstock has the highest specific biogas yield – 22 GJ/dry t and zero energy inputs for biomass treatment. The lowest energy yield coefficient (**2.4**) is for energy crops as a feedstock. This option has the biggest energy inputs for biomass treatment (as it includes energy crops cultivation) and average biogas yield – 10.6 GJ/dry t.

Table 3. Characteristics of the studied biogas technologies [20]

Feedstock	Dry matter content, %	Biogas yield GJ/dry t	Energy inputs, GJ/dry tonne			EYC_{NR}*
			Preparation of feedstock	Transportation of feedstock (15 km)	Transportation of digested remains	
Cow manure	8	6.2	0	0.19	0.15	**2.6**
Pig manure	8	7	0	0.19	0.15	**3.0**
Grease separator sludge	4	22	0	1.2	0.24	**6.2**
Energy crops	23	10.6	1,9	0.07	0.24	**2.4**
Municipal organic waste	30	12.4	0,8	0.24	0.24	**3.6**
Slaughterhouse waste	17	9.4	0	0.14	0.24	**3.6**
Tops and leaves of sugar beet	19	10.6	0,54	0.09	0.24	**3.5**
Straw	82	7.1	0,28	0.05	0.24	**2.7**

** The values are calculated by the authors of the Position Paper on the basis of data [20] for the basic allocation method for the energy inputs.*

Production of bioethanol and biodiesel

There are a lot of debates on the expediency of production of the first generation biofuels, especially bioethanol. It is believed that the energy consumption for the production of bioethanol exceeds the energy content of the resulting biofuel. Let's consider some important papers on this issue.

Energy efficiency of different technologies for bioethanol production (conditions of France) is assessed in the study [8]. Three cases are considered: I – bioethanol production from sugar beet with distillery dreg as a by-product, II – bioethanol production from sugar beet with sugar as by-product[1], III – bioethanol production from wheat grain with dry grain remains with soluble substances as a by-product. Several options for energy demand (i.e. "input" energy) allocation between primary and by-products were analyzed for each case, such as distribution of mass, energy content, market cost or energy for production of by-product substitute ("substituting" energy). Ae

[1] Since the subject of the study is bioethanol, it is conventionally regarded as the main product, and sugar as a by-product.

present there is no consensus of experts regarding what method of "input" energy allocation is the best. But the most often used allocation method is the one by mass of final products.

Calculation results show that Energy Yield Coefficient EYC_{NR} differs substantially for different technologies of bioethanol production, and also depends on how "input" energy is allocated by final products (**Table4**).

Table 4. Energy efficiency of bioethanol production technologies [8]

Allocation method for "input" energy by final products	Bioethanol from sugar beet**			Bioethanol from wheat
	Option **I**	Option 50% **I** / 50% **II**	Option **II**	Option **III**
	$\boldsymbol{EYC_{NR}}$	$\boldsymbol{EYC_{NR}}$	$\boldsymbol{EYC_{NR}}$	$\boldsymbol{EYC_{NR}}$
No allocation – all is referred to bioethanol	1.42	0.54	0.33	0.83
By mass*	**1.59**	**1.28**	**1.02**	**2.23**
By energy content	1.51	1.13	0.89	1.52
By market cost	1.47	1.22	0.98	1.77
By energy for production of by-product substitute	1.48	1.12	0.88	0.96

* *The most common allocation method.*

** *Bioethanol production options*: ***I** – from sugar beet with distillery dreg as a by-product, **II** – from sugar beet with sugar as "by-product", **III** – from wheat grain with dry grain remains with soluble substances as a by-product.*

Biofuel production from sugar beet for all considered options results in EYC_{NR} **< 2**, and if "input" energy isn't allocated by mass of the final products it is even **< 1.** This indicates a *very low energy efficiency of bioethanol production and even its absence.* The only positive result is given by option of bioethanol production from wheat with "input" energy allocation by mass of final products – bioethanol and dry grain. In this case Energy Yield Coefficient EYC_{NR} > **2**[2]**,** that meets minimum energy efficiency requirements for bioenergy technologies.

The study [9] is also of significant interest representing a detailed analysis of an overall energy intensity of bioethanol and biodiesel production under current technologies for Ukrainian conditions. Options of bioethanol production from winter wheat, spring barley and sugar beet are examined. Assessment results show that under vacuum rectification technology energy demand for bioethanol production from all feedstock considered is almost equal to energy content of the produced biofuel ($\boldsymbol{EYC_{NR} \approx 1}$) (**Table. 5**). Energy demand for bioethanol production under atmospheric rectification technology exceeds its energy content ($\boldsymbol{EYC_{NR} < 1}$).

[2] The later study of these authors [17] represents for this option EYC_{NR} = **1.93**. (It is due to fact that earlier the authors attributed to bioethanol 37% of total energy "input", and later they increased this figure to 42.7%). This is additional evidence that production of first-generation bioethanol is on the verge of energy efficiency.

Table 5. Energy indicators of bioethanol production technologies [9]

Feedstock	Cumulative Energy Demand*, MJ/l		**Energy Yield Coefficient EYC_{NR}****	
	Atmospheric rectification *CED 1*	Vacuum rectification *CED 2*	Atmospheric rectification Q_{BE} / *CED 1*	Vacuum rectification Q_{BE} / *CED 2*
Winter wheat	28.58	22.88	0.8	1.0
Spring barley	25.58	19.88	0.9	1.1
Corn	27.39	21.69	0.8	1.0
Sugar beet	29.7	24.3	0.8	0.9

** All technological (physical) energy demands are included. Energy demand connected with human labor, equipment depreciation etc.*

*** Here and further EYC_{NR} is calculated by the authors of the Position Paper according to the data of the study [9]. Calorific value of bioethanol Q_{BE} = 22.5 MJ/l.*

The study also represents that Cumulative Energy Demand for bioethanol production in the USA amounts from 18 MJ/l to 38,2 MJ/l. Considering these parameters, Energy Yield Coefficient $\boldsymbol{EYC_{NR}}$ amounts to **0.59-1.25**, i.e. it is unacceptably low.

So the authors of [9] concluded that *this direction of biofuels production could not be considered as energy appropriate*. It can be used only locally in the case when feedstock for bioethanol production is waste that should be utilized or removed. Or in other words, when energy consumption for feedstock transportation and processing is insignificant and doesn't exceed 4-5 MJ/l.

As for biodiesel fuel, the study [9] considers the case of biodiesel production from rapeseed oil by its trans-esterification with methyl alcohol. Total energy demand for biofuel production is assessed and amounts 23.5-29.3 MJ/kg. Taking into account energy content of biodiesel of 40 MJ/kg, these indicators correspond to Energy Yield Coefficient $\boldsymbol{EYC_{NR}}$ **= 1.36-1.70**, that is significantly lower than minimum figures, recommended in the considered above study [3] ($\boldsymbol{EYC_{NR}}$ **> 2)**. Authors [9] point that taking into account energy equivalent of factors, caused by human labor, depreciation of equipment and buildings, financial and other expenses, total energy consumption of biodiesel production from rapeseed oil will amount 40-50 MJ/kg ($\boldsymbol{EYC_{NR}}$ **= 0.8-1.0**). This means that *biodiesel production is also inappropriate from the energy point of view*.

Environmental analysis

Reduction of green-house gas emissions is one of the most important indicators in environmental assessment of bioenergy technologies. Although biomass is considered CO_2-neutral fuel, but operations of collection, storage, transportation, pre-treatment and utilization consume fossil fuel energy, resulting in GHG emissions. The major green-house gases, which occur during operation of energy systems, are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Amount of all green-house gases is normalized to an equivalent figure of CO_2 emissions by appropriate coefficients.

Below there is a comparison of different bioenergy technologies with installations on fossil fuels subject to reduction of GHG emissions and analysis of its correspondence to requirements of Directive 2009/28/EC [1]. According to this Directive GHG emissions reduction when introducing bioenergy technologies should amount not less than **35%** compared to the same use of fossil fuels. From 01.01.2017 the minimum requirement is increased to **50**%, and from 01.01.2018 – to **60%** for installation entered into operation from 01.01.2017.

Table 6 presents the results of the study [16] that was conducted under Task 38 of the International Energy Agency, own results of the authors of Position Paper and data on typical GHG emissions in the production of liquid biofuels under the Directive 2009/28/EC. The data in the table shows that all the installations for solid biomass and most of the biogas plants meet current and future requirements of the Directive 2009/28/EC, i.e. reducing greenhouse gas emissions caused by their work is > **60%**.

As for liquid biofuels, most parameters of the first generation biodiesel and bioethanol meet current requirements of the Directive 2009/28/EC, some meet the requirement that enters into force from 2017 (min. 50%), and almost all parameters do not meet the requirements, which will be applied from 2018 (min. 60%). For the second-generation biofuels the results are much better as greenhouse gas emissions reduction amounts to **80-95%**. Biogas as transport fuel also has good figures, which are over **80%**.

These results agree well with the data of other authors, collected in the study [16] (**Fig. 5-8**). Reduction of greenhouse gas emissions at energy production from biomass is **70-90%** compared to fossil fuel power plants. When applying the first-generation biofuels, GHG emission reduction is small. Application of bioethanol and biodiesel of the second generation can reduce GHG emissions up to **90%**. Biogas as transport fuel has rather good figures, which are about **65**% on the average.

Table 6. Specific GHG emissions for different biomass-to-energy technologies

Technology type	Specific GHG emissions	Reduction of GHG emissions	
Heat production	g $CO_{2\text{-eq.}}$/kWh_{th}	g $CO_{2\text{-eq.}}$/kWh_{th}	**%**
Wood residues boiler (150 kW_{th}) [16]	52	327	**86%**[1)]
Miscanthus boiler (70 kW_{th}) [16]	101	295	**75%**[1)]
Wood chips boiler (500 kW)[4)]	39	185	**83%**
Energy willow wood chips boiler (300 kW)[4)]	39	185	**83%**
Straw bales boiler (500 kW)[4)]	14	211	**94%**
Wood pellets boiler (100 kW)[4)]	33	194	**85%**
Straw pellets boiler (100 kW)[4)]	60	165	**72%**
Power production	g $CO_{2\text{-eq.}}$/kWh_{el}	g $CO_{2\text{-eq.}}$/kWh_{el}	
Wood chips Power plant (2 MW_{el})[4)]	213	909	**81%**
Straw bales Power plant (2 MW_{el})[4)]	217	905	**80%**
Straw bales Power plant (25 MW_{el}) [19][9)]	178[10)]	no data	**65%**
Wood residues Power plant (30 MW_{el}) [16]	71	950	**93%**[2)]
Power plant 500 MW_e: co-firing of wood residues with coal [16]	128	881	**87%**[2)]
Combined production of heat and power	g $CO_{2\text{-eq.}}$/kWh_{e+th}	g $CO_{2\text{-eq.}}$/kWh_{a+th}	
Biogas plant co-digestion of manure with corn silage (annual power production 4 GW·h, heat production 7,2 GW·h) [16]	266	207	**56%**[3)]
Wood chips CHP plant (2 MW_{el} +10 MW_{th})[4)]	35	152	**81%**
Straw bales CHP plant (2 MW_{el} +10 MW_{th})[4)]	37	150	**80%**
***Transport biofuels** [1]*[5)]	g $CO_{2\text{-eq}}$/MJ		
Biogas from manure[8)]	12-13		**84-86%**
Biogas from MSW landfills[8)]	17		**80%**
1 generation biofuels			
Bioethanol from sugar beet	33		**61%**
Bioethanol from wheat	57		**32%**
Bioethanol from corn	37		**56%**
Bioethanol from rapeseed	46		**45%**
Biodiesel from rapeseed [16]	111 g $CO_{2\text{-eq}}$/km	80 g $CO_{2\text{-eq}}$/km	**58%**[6)]
	157 g $CO_{2\text{-eq}}$/km	34 g $CO_{2\text{-eq}}$/km	**18%**[7)]
Biodiesel from sunflower	35		**58%**
Biodiesel from soybean	50		**40%**
2 generation biofuels			
Bioethanol from wheat straw	11		**87%**
Bioethanol from wood residues	17		**80%**
Biodiesel FT	4-6		**93-95%**

***1)** Compared to oil-fired boiler. **2)** Compared to coal-fired power plant. **3)** Compared to gas-fired CHP plant. **4)** Results of the authors of the Position Paper for Ukrainian conditions (biomass transport distance – 50 km). Comparison with natural gas combustion. **5)** Typical values according with Application 5 of Directive 2009/28/EC [1]. **6)** By-product glycerine is used as a material in food or pharmaceutical industry. **7)** By-product glycerine is used as a fuel. **8)** As the compressed methane. **9)** Data for the case of grain yields of order 7 dry t/ha. Comparison with natural gas combustion. **10)** Recalculation by the authors of the Position Paper based on data from a respective study.*

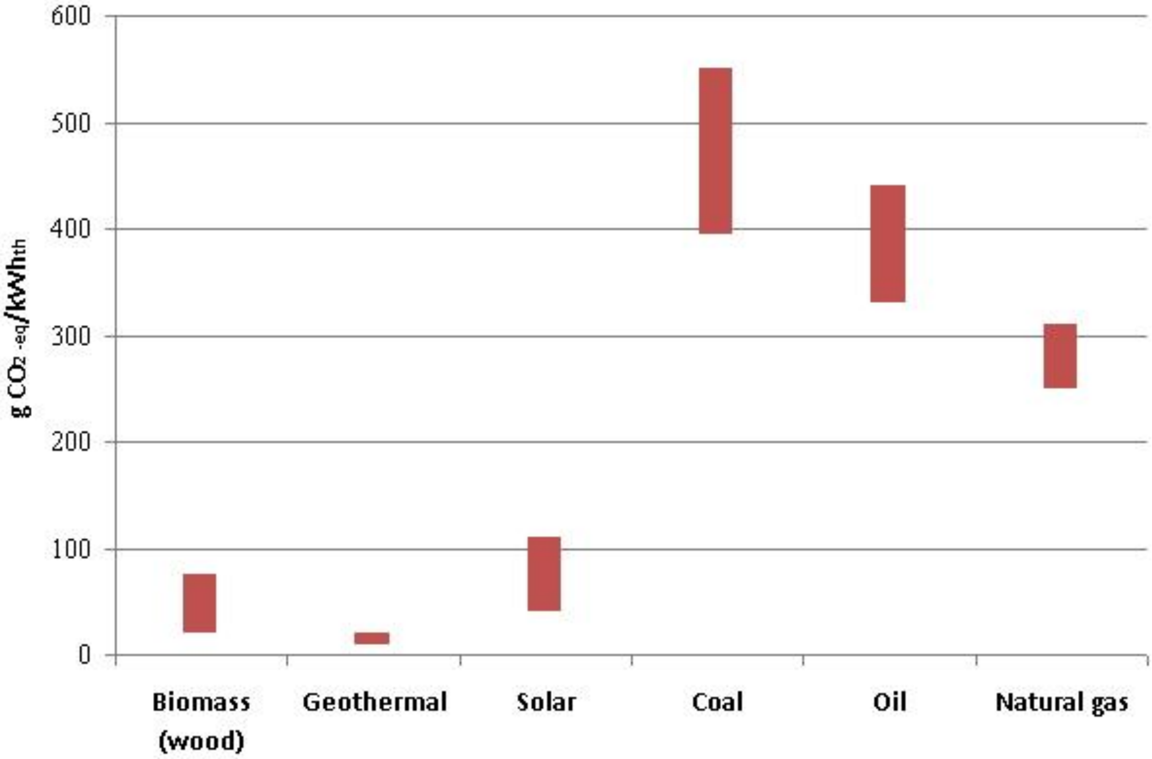
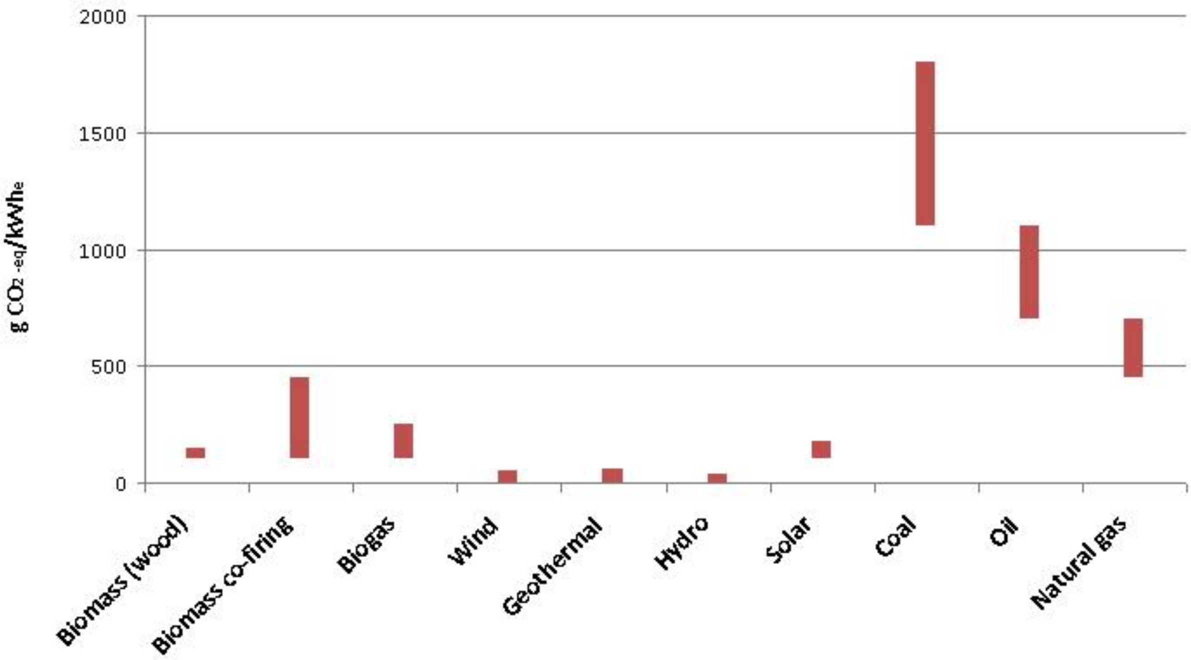


Fig. 5. Specific GHG emissions from heat production [16]



* 5-15% by energy

Fig. 6. Specific GHG emissions from power production [16]

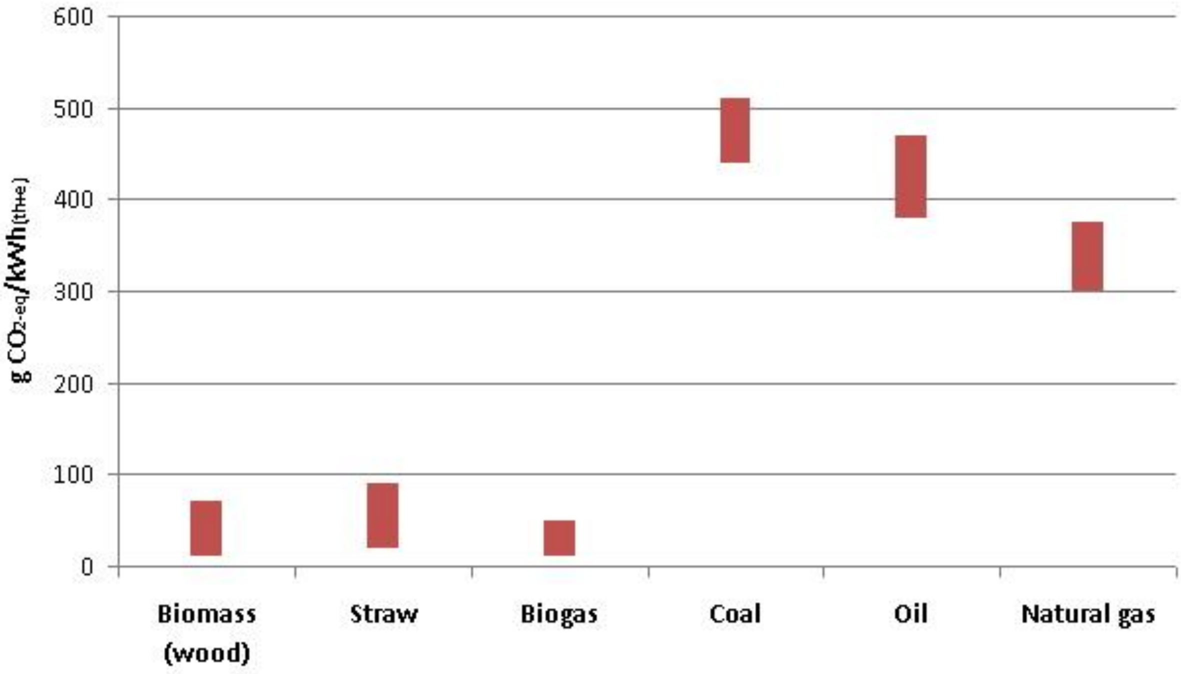


Fig. 7. Specific GHG emissions from combined heat and power production [16]

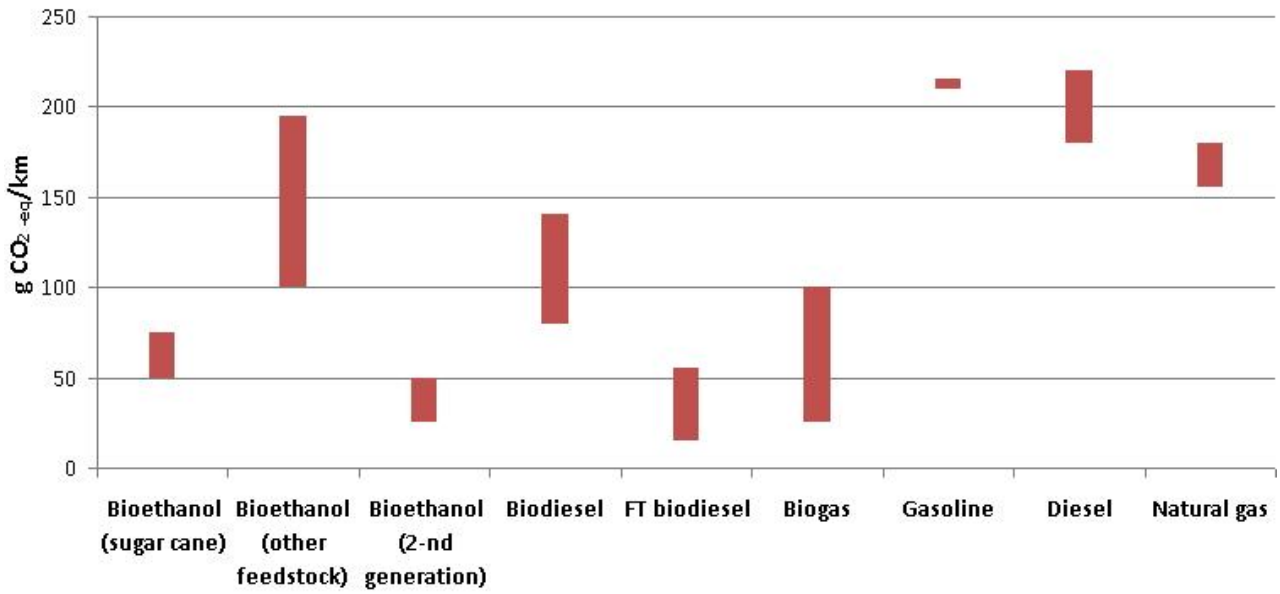


Fig. 8. Specific GHG from transport fuels use [16]

Influence of a transportation distance on energy and environmental indicators of bioenergy technologies

As mentioned above, one of the parameters that considerably influence the energy efficiency of introduction of bioenergy technologies is distance for biomass transportation to the place of processing, end-use etc. It is generally believed that biomass (excluding biomass pellets/briquettes) shouldn't be transported over a distance of 50-100 km (hereafter it comes to motorized transport), but specific literature data on this subject is very limited.

According to data of the study [3], to conserve energy efficiency of bioenergy installations at the minimum required level ($EYC_{NR} > 2$) wood chips can be transported to a distance 200-300 km, and wood pellets have practically no restrictions on the distance. If a pellet power plant must meet the criteria of high energy efficiency ($EYC_{NR} > 5$), the transportation distance is limited to about 1200 km.

For more information, the authors of the Position Paper examined the impact of biomass/biofuel transport distance on Energy Yield Coefficient EYC_{NR} for Ukrainian conditions. The results of calculations for typical installations showed that baled straw, wood chips and biomass pellets can be transported to a distance of 300 km retaining a sufficiently high rate of Energy Yield Coefficient ($EYC_{NR} > 2$) (**Fig. 9**).

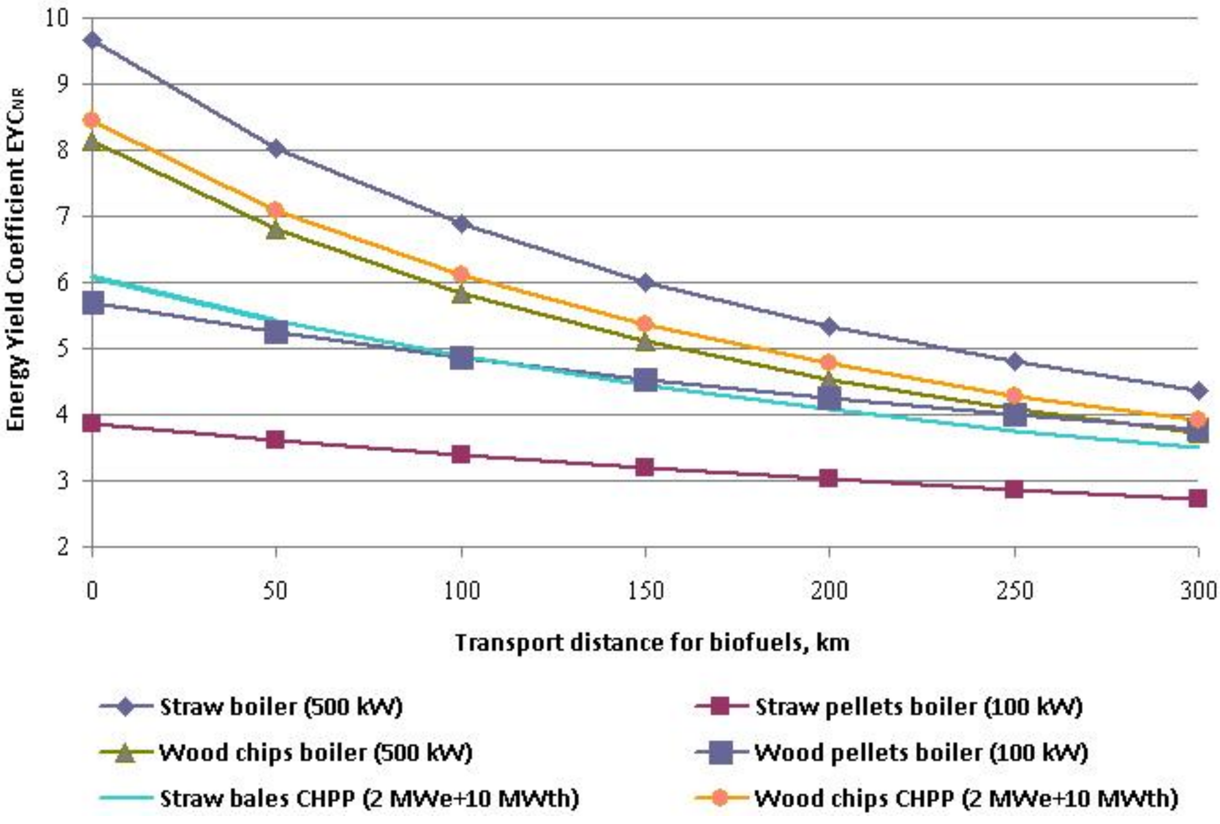


Fig. 9. Influence of the transport distance for biofuels at Energy Yield Coefficient

Boundary transportation distance that correspond to $EYC_{NR} = 1$, $EYC_{NR} = 2$ and $EYC_{NR} = 5$ are presented in **Table 7**. If Energy Yield Coefficient equals to **1**, it means that (non-renewable) energy demand for production and operation of bioenergy installation equals to the produced energy "output". EYC_{NR} = **2** corresponds to the minimum acceptable energy efficiency of the installation, and EYC_{NR} = **5 and over** corresponds to the most recommended values (according to data from study [3]).

Table 7. Maximum feasible distance for transportation of biofuels.

Type of energy installation	Boundary transportation distance, km		
	EYC_{NR} = 1 *energy input is equal to energy outpu*	***EYC_{NR} = 2*** *allowable minimum*	***EYC_{NR} = 5*** *recommended value*
Wood chips boiler (500 kW)	1800	800	170
Energy willow wood chips boiler (300 kW)	2100	900	120
Wood pellets boiler (100 kW)	2800	1100	80
Wood chips CHP plant (2 MW_{el}+10 MW_{th})	1900	850	170
Wood chips Power plant (2 MW_{el})	250	0	-*
Straw boiler (500 kW)	1800	800	200
Straw pellets boiler (100 kW)	1800	500	-*
Baled straw CHP plant (2 MW_{el} +10 MW_{th})	1500	800	80
Baled straw Power plant5 (2 MW_{el})	150	-**	-*

** Even at zero distance of biofuel transportation EYC_{NR} < 5.*

*** Even at zero distance of biofuel transportation EYC_{NR} < 2.*

The table presents just a few typical examples (the authors have the calculation results for power plants of different capacities), but they clearly reflect the overall picture. For the case when bioenergy installation is operated (except Power plants) at energy efficiency level not lower than recommended minimum (EYC_{NR} > 2), then transportation distance for biofuels can be quite large - **500-1000 km** depending on the type of biofuel and type of installation. To provide a higher level of energy efficiency (EYC_{NR} > 5), the distance of transportation should be limited to **100-200 km**, and in some cases to a minimum possible value.

It should be noted that conclusions made are of general nature, and in each particular case it is necessary to perform detailed calculations with thorough consideration of local conditions.

Conclusions

Introduction of bioenergy technologies offers ample opportunities for substituting fossil fuels. Feasibility and priority of introducing certain technologies in concrete conditions can be determined based on calculation results for energy balance and GHG emissions balance, which are the main elements of the life cycle assessment of technologies.

Analysis of literature data and own calculation results indicates high energy efficiency of heat energy production technologies from solid biomass. All of the considered boiler installations have the Energy Yield Coefficient ***EYC_{NR}* > 2** (i. e. greater than recommended minimum), and the majority has ***EYC_{NR}* > 5**, that meet recommended maximum. Solid biomass CHP plants also have high energy performance – all considered cases have ***EYC_{NR}* > 5**. Generation of just electricity from solid biomass has notably lower energy efficiency compared to combined heat and power production. For the most considered power plants the Energy Yield Coefficient amounts **less or about 2** depending on the biomass type and other conditions.

The energy efficiency of biogas plants greatly depends on the type of raw materials, applied technology and other conditions. According to available literature data, EYC_{NR} is from **2** to > **6** for biogas plants.

Situation with the production of biofuels (biodiesel and bioethanol) is ambiguous. For most of the available data Energy Yield Coefficient for them is significantly **below 2**, while some authors show $\boldsymbol{EYC_{NR}}$ **> 2**. It seems that positive result from the energy point of view can be achieved only in some cases, under certain conditions, such as use of raw materials defined as "waste for disposal".

Concerning the environmental efficiency of bioenergy technologies it can be noted that all solid biomass installations and most of biogas plants meet current and future requirements of the Directive 2009/28/EC – greenhouse gas emissions reduction caused by their operation is **> 60%**.

As for liquid biofuels, most parameters of the first generation biodiesel and bioethanol meet current requirements of the Directive 2009/28/EC, some meet the requirement that enters into force from 2017 (min. **50%**), and almost all parameters exceed the requirements that will be applied from 2018 (min. **60%**). For second-generation biofuels results are much better, greenhouse gas emissions reduction amounts to **80-95%**. Biogas as transport fuel also has good figures, which are **over 80%**.

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Abbreviation

CFB – circulating fluidized bed;
CHP – combined heat and power;

DH – district heating;
EYC_{NR} – Energy Yield Coefficient;
EF – entrained flow;
ETBE – ethyl tertiary butyl ether;
FT – Fisher-Tropsch;
GHG – greenhouse gas;
TPP – thermal power plant;
Q_{BE} – bioethanol heating value;
RE – renewable energy;
RES – renewable energy sources;
RME – rape methyl ester;
SRC – short rotation coppice;
TPP – thermal power plant;
kgoe – kg of oil equivalent;
odt – oven dry tonne.

Previous UABIO's publications

http://www.uabio.org/activity/uabio-analytics

1. Position Paper N 1 "Position of bioenergy in the draft updated energy strategy of Ukraine till 2030".
2. Position Paper N 2 "Analysis of the Law of Ukraine "On amending the Law of Ukraine «On Electricity" No5485-VI of 20.11.2012".
3. Position Paper N 3 "Barriers to the development of bioenergy in Ukraine".
4. Position Paper N 4 "Prospects of biogas production and use in Ukraine".
5. Position Paper N 5 "Prospects for the electricity generation from biomass in Ukraine"
6. Position Paper N 6 "Prospects for heat production from biomass in Ukraine"
7. Position Paper N 7 "Prospects for the use of agricultural residues for energy production in Ukraine".

Civic union "Bioenergy Association of Ukraine" (UABio) was established to create a common platform for cooperation on bioenergy market in Ukraine, as well as to provide the most favorable business environment, accelerated and sustainable development of bioenergy. General constituent assembly of UABio was held on September, 25, 2012 in Kyiv. The Association was officially registered on 8 April 2013. Among UABio members there are over 10 leading companies and over 20 recognized experts working in the field of bioenergy.

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