Original scientific paper
Journal of Central European Agriculture, 2021, 22(2), p.397-407
DOI: /10.5513/JCEA01/22.2.3076

Researching of indicators of agroecosystem without external energy supply

Gennadii GOLUB[1], Vyacheslav CHUBA[1], Vitaliy LUTAK[2], Yaroslav YAROSH[3], Savelii KUKHARETS[3] (✉)

[1] National University of Life and Environmental Sciences of Ukraine, Department of tractors, automobiles and bioenergosystems, Heroyiv Oborony st., 15, Kyiv, 03041, Ukraine

[2] Ministry of Education and Science of Ukraine, Main department of higher education, Victory Avenue, 10, Kyiv, 01135, Ukraine

[3] Polissia National University, Department of Mechanics and Agroecosystems Engineering, Staryi Blvd 7, Zhytomyr, 10008, Ukraine

✉ Corresponding author: kikharets@gmail.com

Received: October 21, 2020; accepted: February 3, 2021

ABSTRACT

The agroecosystem without external energy supply can provide compensation for the needs of the agroecosystem in liquid fuel, heat and electricity at the expense of plant biomass as a renewable energy source. Based on the analysis of the energy balance of the agroecosystem, the area under rapeseed needed for biodiesel production and the area under crops needed for bioethanol production were calculated for the needs of the agroecosystem, as well as additional quantities of straw to compensate for the loss of humus in crop rotation, which sets the amount of plant biomass that can be used to produce heat and electricity using cogeneration gas plants. It was found that the average typical needs of the agroecosystem in diesel fuel from 60 to 80 kg/ha, and the ratio of the area under rapeseed needed for biodiesel production for the needs of agroecosystem to the total area of crop rotation with grain yield of canola from 1500 to 2500 kg/ha is from 8.3 to 18.5%. At the average typical demand of the agroecosystem for gasoline is from 15 to 16 kg/ha, the ratio of the area under wheat, barley and corn required to produce bioethanol for the needs of the agroecosystem to the total area of crop rotation with a crop yield of 3000 to 5000 kg/ha is from 0.7 to 0.9%. The increase in grain yield from 3000 to 5000 kg/ha causes an increase in the supply of organic matter to soil to a greater extent than its mineralization, and accordingly, the deficit of organic matter and humus decreases from 507 to 180 kg/ha, the volume of plant biomass (mainly straw) to compensate for the deficit of organic matter and humus decreases from 1867 to 217 kg/ha, which causes an increase in the possible volumes of plant biomass for energy production for sale from 27 to 2963 kg/ha. Respectively, electricity production increases from 48 to 2301 kWh/ha and heat power from 0 to 25,5 GJ/ha, while providing its own needs for heat and electricity by burning biogas in a cogeneration plant.

Keywords: crop rotation, plant biomass, biodiesel, bioethanol, generator gas, energy balance

INTRODUCTION

The use of renewable energy sources reduces greenhouse gas emissions (Garlucci et al., 2015; Harrous et al., 2017). Agricultural production is a complex agroecosystem (Belcher et al., 2004; Kang et al., 2015; Golub et al., 2017), which is constantly affected by human production activities (Conway, 1987; Moonen and Barberi, 2008; Preston et al., 2015). Traditionally, the structure of the agroecosystem is made up of crop production (based on crop rotation) and livestock (Harrous et al., 2017; Golub et al, 2020a). This agroecosystem requires the supply of diesel fuel, gasoline, heat and electricity carriers to meet energy needs (Sami et al., 2013) (Figure 1).

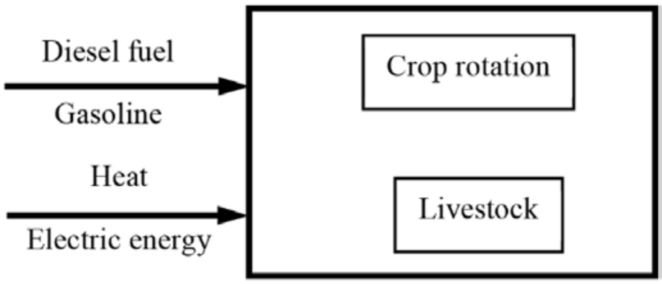

Figure 1. Structure of the traditional agroecosystem

However, recently scientists have expanded the concept of agroecosystem. They believe that it is possible to efficiently produce several types of biofuels within the modern agro-system (Ryabchenko et al., 2017, Yakubiv, 2020), namely biogas, generator gas, diesel biofuels, bioethanol, fuel pellets and briquettes (Melece and Krievina, 2016; Matin et al., 2018; Siegmeier et al., 2019; Golub et al, 2020a). In this case, the agroecosystem does not need energy carriers supply, and can even provide excess of electricity production for sale (Figure 2). Such an agroecosystem can be called energetically autonomous (Golub et al, 2020a).

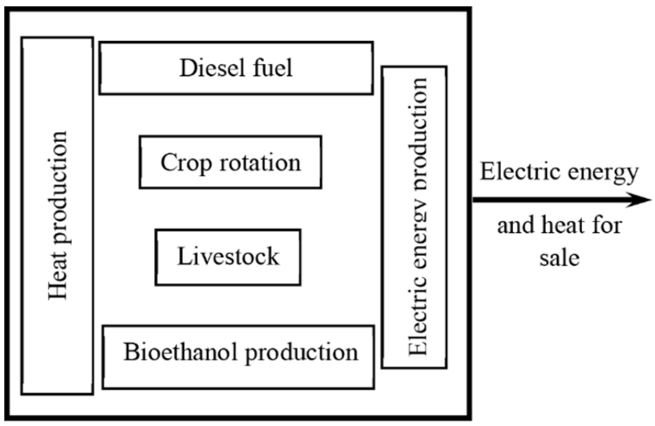

Figure 2. Structure of the agroecosystem without external energy supply

The main raw material for biofuel production in the agroecosystem is plant biomass (Verdade et al., 2015; Çakan et al., 2019; Golub et al, 2020a; Prasad et al., 2020). However, the intensive use of plant-based biomass causes concern among scientists regarding the reduction of food production and the negative impact on the soil environment (Koizumi, 2013; Araujo Enciso et al., 2016; Javed et al., 2018; Mockshell and Villarino, 2019; Subramaniam et al., 2019). However, scientists make such conclusions mainly based on the results of statistical data processing.

Several scientists are trying to reconcile the needs of the agroecosystem in energy with the possibility of obtaining it. In the work by Wasiak (2017) using the model of energy balance of biofuel production, it is concluded that one matrix of the cultivated area can provide the energy for 5 to 100 units of the same area. However, the author does not indicate how this indicator will affect the use of crop residues. In addition, there is an open issue about the balance of humus. In the paper by Orynycz (2017), the efficiency of biodiesel production from rapeseed is studied using energy balances. In the article by Rodias et al. (2019), the energy balance model is used to match the cost of growing energy crops with the amount of energy received from them. However, such studies do not allow for a conclusion about the efficiency of biofuel production for the entire agroecosystem, because the needs of the entire agroecosystem for fuel and energy are not considered. Fredriksson et al. (2006) evaluated the energy efficiency of the production of various types of biofuels, but it was not established how changes in the production of one type of fuel affect the other. Using the energy balance, the efficiency of diesel biofuel production (Fore et al., 2011) and biogas production (Jankowski et al., 2020) in agroecosystem was evaluated, but these studies also do not consider the impact of other fuels production and the use of biomass for other needs.

We believe that when creating an energy balance model, it is necessary to consider the needs of the agroecosystem for fuel and energy and take into account the impact of the level of production of one type of fuel on another. Given that biomass is the main source for biofuel production (Verdade et al., 2015; Golub et al, 2020a), the energy balance equation should also take into account the balance of plant biomass in the agroecosystem.

The aim of this study is to determine the indicators of agroecosystem without external energy supply based on the analysis of their energy balance, in which it is possible to provide compensation for the needs of the agroecosystem in liquid fuel, heat and electricity from plant biomass as a renewable energy source. The novelty of the research is the method of calculation of the ratio of the area under rapeseed needed for the production of biodiesel and the area under wheat, barley and corn necessary for the production of bioethanol for the needs of agroecosystem to the total area of crop rotation, as well as additional quantities of straw to compensate for the loss of humus in crop rotation that allows setting the amount of plant biomass that can be used for excess heat and energy production for sales to third parties by using cogeneration gas plant.

MATERIALS AND METHODS

Based on the well-known principles of recording energy balances (Orynycz, 2017; Wasiak, 2017), the overall energy balance of an agroecosystem will have the following form:

$$Q_{DF} = Q_{DBF};\; Q_G = Q_{BE};\; \sum_{i=1}^{n} Q_i^{TE} = Q_{BG}^{TE} + Q_{DBF}^{TE} + Q_{StBP}^{TE} + Q_{St}^{TE};$$

$$\sum_{i=1}^{n} Q_i^{EE} = Q_{BG}^{EE} + Q_{DBF}^{EE} + Q_{StBP}^{EE}, \tag{1}$$

where

Q_{DF}, Q_G – energy equivalent of the typical agroecosystem demand for diesel and gasoline, MJ;

Q_{DBF}, Q_{BE} – energy equivalent of diesel biofuels and bioethanol produced for the needs of the agroecosystem, MJ;

$\sum_{i=1}^{n} Q_i^{TE}, \sum_{i=1}^{n} Q_i^{EE}$ - the total demand of all technological processes in the agroecosystem for heat and electricity, MJ;

$Q_{BG}^{TE}, Q_{BG}^{EE}, Q_{DBF}^{TE}, Q_{DBF}^{EE}, Q_{StBP}^{TE}, Q_{StBP}^{EE}$ on of heat and electricity from biogas, diesel biofuels and straw briquettes and pellets, MJ;

Q_{St}^{TE} – production of heat energy from baled straw, MJ.

These equations should be supplemented with the balance equation of plant biomass in the agroecosystem, since the production of heat and electricity from straw briquettes and pellets, as well as from straw, depends on the amount of straw that can be used for thermal needs.

Production of thermal energy from straw is included in the system because such production is the easiest to implement when using solid fuel boilers and energy bales of straw.

The balance equation of plant biomass will have the following form:

$$St_E = St_{CR} + GW - St_L - BM_{CH} - St_{LP} + St_{LC} - St_{MP} - St_{AH}, \tag{2}$$

where St_E – the amount of plant biomass that can be used in the agroecosystem for thermal needs and power generation, t; St_{CR} – total amount of straw produced in the agroecosystem, t; GW – the amount of plant biomass in the form of grain waste, which is the waste of grain cleaning, t; St_L – the amount of straw that is lost during harvesting, t; BM_{CH} the amount of plant biomass that remains in crop rotation fields to compensate for the loss of humus in the form of crushed corn residues, t; St_{LP}, St_{LC}, St_{MP} – the amount of straw that is used for bedding in pig and dairy farming, as well as used for the production of mushroom products, t; St_{AH} – additional amount of straw that is used to compensate for the loss of humus in the crop rotation, t.

All components of this equation have a clear definition, except for the additional amount of straw that is lost to compensate for the loss of humus in crop rotation. To determine this value, you need an additional equation that determines the balance of humus in the crop rotation:

$$D_H = H_{PBM} - M_{HCR} + \sum_{j=1}^{m} H_j \left(1 - \frac{W_j}{100}\right) k_{Hj} + St_{AH} \left(1 - \frac{W_{St}}{100}\right) k_{HSt} = 0 \tag{3}$$

where D_H – the deficit of humus in crop rotation, t; H_{PBM} – receipt of humus in the crop rotation due to the humification of plant biomass remaining in the fields, t; M_{HCR} – total salinity of humus in crop rotation when growing crop rotation crops per year, t; H_j – humus receipt in the crop rotation due to the humification of plant biomass entering the fields (plant biomass of siderates, weeds, compost and waste substrate after growing mushrooms), t; W_j, W_{St} – relative humidity of plant biomass entering the fields (plant biomass of siderates, weeds, compost and waste substrate after growing mushrooms), as well as straw, %; k_{Hj}, k_{HSt} – the coefficient of humification of plant biomass entering the fields (plant biomass of siderates, weeds, compost and waste substrate after growing mushrooms), as well as straw, rel. un.

From this equation, the additional amount of straw that is used to compensate for the loss of humus in the crop rotation will be:

$$St_{AH}=\frac{M_{HCR}-H_{PBM}-\sum_{j=1}^{m}H_j\left(1-\frac{W_j}{100}\right)k_{Hj}}{\left(1-\frac{W_{St}}{100}\right)k_{HSt}} \quad (4)$$

In these equations, it is advisable to substitute the values of the component quantities that determine the energy indicators of the autonomous agroecosystem (Table 1).

Table 1. Values of component values that determine the energy indicators of an autonomous agroecosystem

Indicator	Value
The energy equivalent of the typical agroecosystem demand for diesel fuel	$Q_{DF}=\alpha_{DF}S_{CR}\gamma_{DF}$
Q_{DF} – typical demand of the agroecosystem for diesel fuel, kg/ha; S_{CR} – total area of crop rotation, ha; γ_{DF} – calorific value of diesel fuel, MJ/kg	
Energy equivalent of diesel biofuel produced for the needs of the agroecosystem	$Q_{DBF}=m_{RS}k_Ok_{DBF}\gamma_{DBF}=Y_Rk_{RS}S_Rk_Ok_{DBF}\gamma_{DBF}$
m_{RS} – the mass of rapeseed necessary for the production of diesel biofuels for the needs of the agroecosystem, kg; k_O – the ratio of the yield of oil from rapeseed, rel. un.; k_{DBF} – coefficient of diesel biofuel output from oil, rel. un.; γ_{DBF} – calorific value of diesel biofuel, MJ/kg; Y_R – the yield of rapeseed, kg/ha; k_{RS} – the yield ratio of rapeseed, rel. un.; S_R – the area under rapeseed necessary for the production of diesel biofuels for the needs of the agroecosystem, ha	
Energy equivalent of the typical agroecosystem demand for gasoline	$Q_G=\alpha_GS_{CR}\gamma_G$
α_G – typical agroecosystem demand for gasoline, kg/ha; γ_G – calorific value of gasoline, MJ/kg	
Energy equivalent of bioethanol produced for the needs of the agroecosystem	$Q_{BE}=\begin{pmatrix}Y_Wk_{WS}S_Wk_{BEW}+\\+Y_Bk_{BS}S_Bk_{BEB}+\\+Y_Ck_{CS}S_Ck_{BEC}\end{pmatrix}\gamma_{BE}$
k_{BEW}, k_{BEB}, k_{BEC} – the coefficients of the output of bioethanol from wheat, barley and corn, rel. un.; γ_{BE} – calorific value of bioethanol, MJ/kg; Y_W, Y_B, Y_C – wheat, barley and corn yields, kg/ha; k_{WS}, k_{BS}, k_{CS}, – the coefficients of wheat, barley and corn output, rel. un.; S_W, S_B, S_C – the area under wheat, barley and corn required for the production of bioethanol for the needs of the agroecosystem, ha	
Total demand of all technological processes of the agroecosystem for heat energy	$\sum_{i=1}^{n}Q_i^{TE}=\sum_{i=1}^{n}\gamma_{TEi}P_i$
γ_{TEi} – the specific thermal energy demand, MJ/thous. un. in egg production, MJ/m^3 in biogas production, MJ/t in the production of other products; P_i – the volume of production or processing of products in the agroecosystem, thous. un. in egg production, m^3 in biogas production, t in the production of other products	
Total demand of all technological processes of the agroecosystem for electricity	$\sum_{i=1}^{n}Q_i^{EE}=\sum_{i=1}^{n}\gamma_{EEi}P_i$
γ_{EEi} – specific electricity demand, MJ/thous. un. in egg production, MJ/m^3 in biogas production, MJ/t in the production of other products	
Production of heat and electricity from biogas	$Q_{BG}^{TE}=V_{BG}k_M\gamma_M\eta_{BG}^{TE}\left(1-k_{ON}^{TE}\right)$; $Q_{BG}^{EE}=V_{BG}k_M\gamma_M\eta_{BG}^{EE}\left(1-k_{ON}^{EE}\right)$
V_{BG} – the biogas yield, m^3; k_M – methane content in biogas, rel. un.; γ_M – heat of methane combustion, MJ/m^3; η_{BG}^{TE}, η_{BG}^{EE} – relative output of heat and electricity when running a biogas cogenerator, rel. un.; k_{ON}^{TE}, k_{ON}^{EE} – relative consumption of heat and electricity for own needs, rel. un.	
The production of heat and electric power from biodiesel	$Q_{DBF}^{TE}=M_{DBF}\gamma_{DBF}\eta_{DBF}^{TE}$; $Q_{DBF}^{EE}=M_{DBF}\gamma_{DBF}\eta_{DBF}^{EE}$
M_{DBF} – the amount of diesel biofuels for heat and electricity generation, kg; η_{DBF}^{TE}, η_{DBF}^{EE} – relative output of heat and electricity when running a cogenerator on diesel biofuel, rel. un.	
Production of heat energy from baled straw	$Q_{St}^{TE}=St_{TE}\gamma_{St}\eta_{BSt}$
St_{TE} – volume of baled straw to compensate for the thermal needs of the agroecosystem, t; γ_{St} – heat of straw combustion, MJ/t; η_{BSt} – efficiency of the boiler for burning plant biomass, rel. un.	
Production of heat and electricity from straw briquettes and pellets using a gas generator	$Q_{StBP}^{TE}=St_{GG}k_{GG}\gamma_{GG}\eta_{GG}^{TE}$; $Q_{StBP}^{EE}=St_{GG}k_{GG}\gamma_{GG}\eta_{GG}^{EE}$

 DOI: /10.5513/JCEA01/22.2.3076

Continued.

Indicator	Value
St_E – St_{TE} = St_{GG} – the number of straw briquettes and pellets for the needs of heat and electricity production using a gas generator, t; k_{GG} – coefficient of generator gas output from straw briquettes and pellets, m^3/t; γ_{GG} – heat of generator gas combustion from straw briquettes and pellets, MJ/m^3; $\eta_{GG}^{TE}, \eta_{GG}^{EE}$ – relative output of heat and electricity when the cogenerator is running on generator gas from straw briquettes and pellets, rel. un.	

Indicators that characterize the balance of plant biomass in the agroecosystem are shown in Table 2. At the same time, it is accepted that in order to partially compensate for the loss of humus in the fields of crop rotation, it is advisable, in addition to the straw lost during harvesting, to leave plant biomass in the form of crushed corn residue.

Table 2. The equation of balance of plant biomass in the agro-ecosystem

Indicator	Value
Total amount of straw produced in the agroecosystem	$St_{CR} = Y_W S_W k_{StW} + Y_B S_B k_{StB} + Y_C S_C k_{StC} + Y_R S_R k_{StR}$
k_{StW}, k_{StB}, k_{StC}, k_{StR} – coefficient of biological yield of wheat, barley, corn and rapeseed straw in relation to the amount of grain, rel. un.	
The amount of plant biomass in the form of grain waste, which is the waste of grain cleaning	$GW = (Y_W S_W + Y_B S_B + Y_C S_C + Y_R S_R) k_{GW}$
k_{GW} – the yield coefficient of grain waste during the cleaning of wheat, barley, corn and rapeseed in relation to the amount of grain, rel. un.	
The amount of straw that is lost during harvesting of the crop rotation	$St_L = (Y_W S_W k_{StW} + Y_B S_B k_{StB} + Y_R S_R k_{StR}) k_{StL}$
k_{StL} – the coefficient of straw loss on stubble and during harvest in relation to the biological straw yield, rel. un.	
The amount of plant biomass that remains in crop rotation fields to compensate for the loss of humus in the form of crushed corn residues	$BM_{CH} = Y_C S_C k_{StC}$
The amount of straw that is used for bedding in pig farming	$St_{LP} = \tau_{LP} q_{LP} n_P$
q_{LP} – specific consumption of straw for litter for pigs, t/(un. day); n_P – average annual number of pigs, un.; τ_{LP} – number of days of litter used for pigs	
The amount of straw used for bedding in dairy farming	$St_{LC} = \tau_{LC} q_{LC} n_C$
q_{LC} – specific consumption of straw for bedding for cows, t/(un. day); n_C – average annual number of cows, un. τ_{LC} – number of days of litter used for cows	
The amount of straw that is used for the production of mushroom products	St_{LC} – is determined by the volume of mushroom production

Thus, taking into account the above dependencies, the overall energy balance of an agroecosystem will have the following form:

$$
\begin{cases}
\alpha_{DF} S_{CR} \gamma_{DF} = Y_R k_{RS} S_R k_O k_{DBF} \gamma_{DBF}; \\
\alpha_G S_{CR} \gamma_G = (Y_W k_{WS} S_W k_{BEW} + Y_B k_{BS} S_B k_{BEB} + Y_C k_{CS} S_C k_{BEC}) \gamma_{BE}; \\
\sum_{i=1}^{n} \gamma_{TEi} P_i = V_{BG} k_M \gamma_M \eta_{BG}^{TE} \left(1 - k_{ON}^{TE}\right) + M_{DBF} \gamma_{DBF} \eta_{DBF}^{TE} + St_{GG} k_{GG} \gamma_{GG} \eta_{GG}^{TE} + \\
+ St_{TE} \gamma_{St} \eta_{BSt}; \\
\sum_{i=1}^{n} \gamma_{EEi} P_i = V_{BG} k_M \gamma_M \eta_{BG}^{EE} \left(1 - k_{ON}^{EE}\right) + M_{DBF} \gamma_{DBF} \eta_{DBF}^{EE} + St_{GG} k_{GG} \gamma_{GG} \eta_{GG}^{EE}; \\
St_E = St_{GG} + St_{TE} = Y_W S_W \left(k_{GW} + k_{StW}\left(1 - k_{StL}\right)\right) + Y_B S_B \left(k_{GW} + k_{StB}\left(1 - k_{StL}\right)\right) + \\
+ Y_R S_R \left(k_{GW} + k_{StR}\left(1 - k_{StL}\right)\right) + Y_C S_C k_{GW} - \tau_{LP} q_{LP} n_P - \tau_{LC} q_{LC} n_C - St_{MP} - \\
- \dfrac{M_{HCR} - H_{PBM} - \sum_{j=1}^{m} H_j \left(1 - \dfrac{W_j}{100}\right) k_{Hj}}{\left(1 - \dfrac{W_{St}}{100}\right) k_{HSt}}.
\end{cases}
\quad (5)
$$

For an agroecosystem without livestock production, this system is somewhat simplified due to the absence of indicators such as production of heat $M_{DBF}\gamma_{DBF}\eta_{DBF}^{TE}=0$ and electric energy $M_{DBF}\gamma_{DBF}\eta_{DBF}^{EE}=0$ from diesel biofuels and the lack of need to spend straw on bedding in pig and dairy farming $St_{LP}+St_{LC}=\tau_{LP}q_{LP}n_P+\tau_{LP}q_{LP}n_P=0$. In addition, in this agroecosystem there is no need to spend baled straw for heat needs $St_{TE}=0$, because heat needs are compensated by the operation of heat engines of electric generators.

To calculate the volume of electricity production for own needs and sales, due to the gasification of straw pellets, it is necessary to perform calculations based on a significant number of parameters of the agroecosystem. To partially simplify the calculations, we will use the parameters of the agroecosystem without livestock production, which is shown in Figure 3.

For a given area and crop rotation structure, according to the equations given in Table 2, the following were calculated: the total amount of straw produced in the agroecosystem St_{CR}; the amount of plant biomass in the form of a grain heap, which is a waste of grain cleaning GW; the amount of straw that is lost during harvesting St_L; the amount of plant biomass that remains in crop rotation fields to compensate for the loss of humus BM_{CH}; the amount of straw that is used for the production of mushroom products St_{MP} St_{MP} and according to the equation (4) an additional amount of straw that remains to compensate for the loss of humus in the crop rotation St_{AH}. Based on the balance of plant biomass, for the fifth equation of the system (5), the amount of plant biomass that can be used in the agroecosystem for thermal needs and electricity production was determined St_E St_E. In general, the volume of electricity and heat for sale to other consumers was determined based on the resources of plant biomass of agroecosystem.

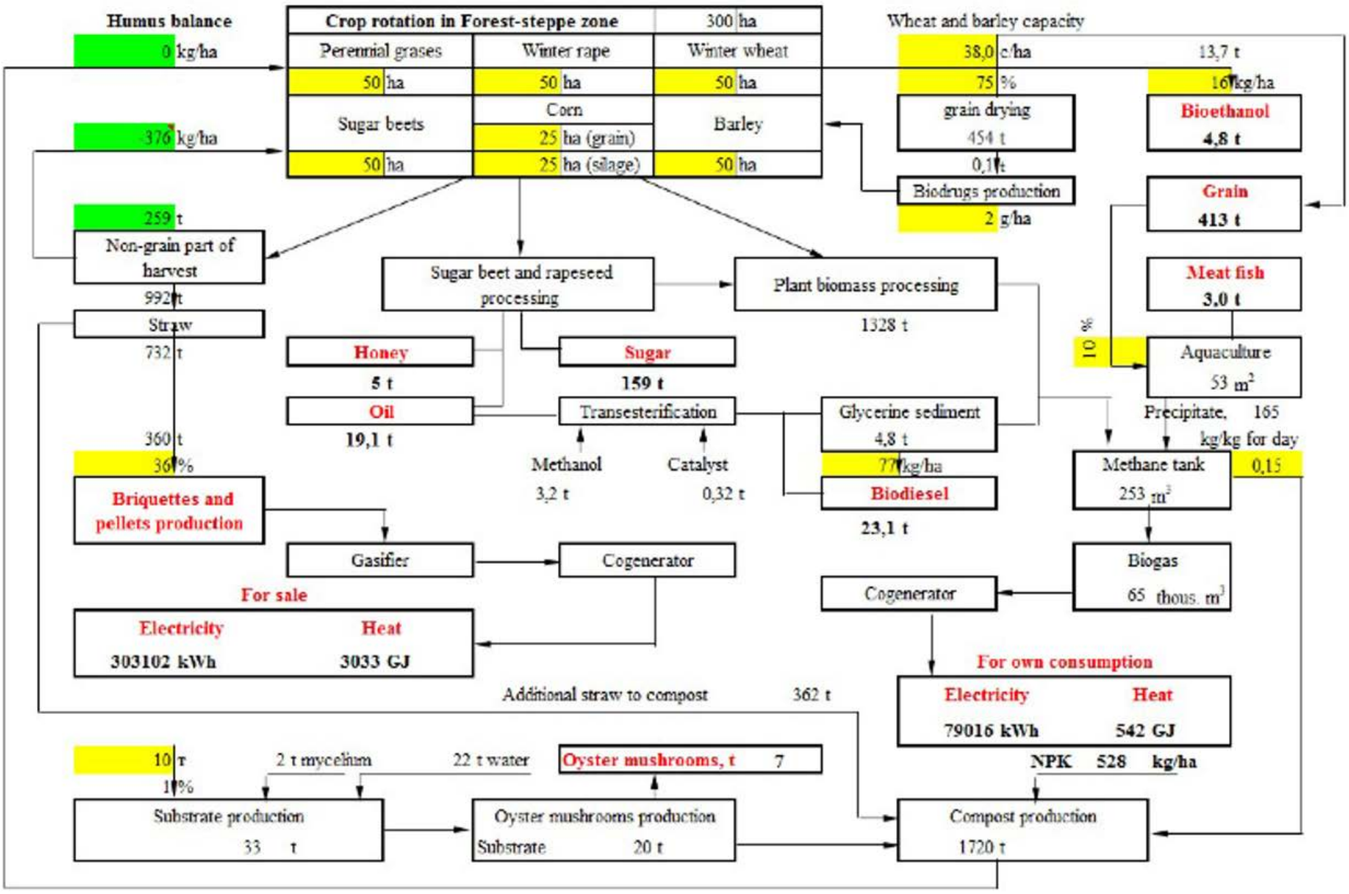

Figure 3. Model of an agroecosystem without external energy supply and with the ability to sell excess heat and electricity

RESULTS AND DISCUSSION

The main principle of solving the above system of equations describing the overall energy balance of an agroecosystem without external energy supply is a given sequence of solutions to individual equations of the system. First, it is possible to find a solution to the first two equations of the system, which relate to covering the needs for diesel biofuels and bioethanol, since they have a rather weak correlation with other equations of the system.

From the comparison of the energy equivalents of the typical needs of agroecosystem in diesel fuel and biodiesel produced for the needs of the agroecosystem, the received ratio of the area under rapeseed needed for biodiesel production for the needs of agroecosystem to the total area of crop rotation will be:

$$\frac{S_R}{S_{CR}} = \frac{\alpha_{DF}\gamma_{DF}}{Y_R k_{RS} k_O k_{DBF}\gamma_{DBF}} \quad (6)$$

The graphical dependence of the ratio of the area under rapeseed needed for biodiesel production for the agroecosystem needs to the total area of crop rotation on the yield of rapeseed and typical need of the agroecosystem in diesel fuel, for clarity, is shown in Figure 4.

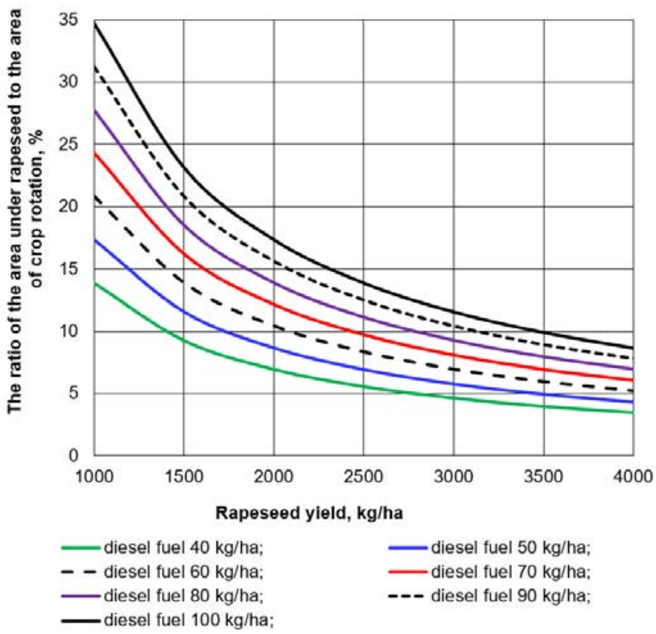

Figure 4. The dependence of the ratio of the area under rapeseed needed for biodiesel production for the needs of agroecosystem for total area of crop rotation to the typical needs of the agroecosystem in diesel fuel and rapeseed yield

Thus, at the average typical need of the agroecosystem in diesel fuel from 60 to 80 kg/ha the ratio of the area under rapeseed needed for biodiesel production for the needs of agroecosystem for the total area of crop rotation with grain yield of rapeseed from 1500 to 2500 kg/ha is from 8.3 to 18.5%, or in average from 10.4% to 13.9%, which is less than the area of one field in a six-field crop rotation. This is consistent with the research presented by Seth (2011), Orynycz (2017) and Wasiak (2017).

It should also be noted that the specific consumption of diesel fuel tends to decrease annually due to increased efficiency of equipment in agricultural production.

From comparing the energy equivalents of the typical needs of the agroecosystem in gasoline and bioethanol produced for the needs of the agroecosystem, we will get the ratio of the area under wheat, barley and corn, with their equal value, necessary for the production of bioethanol for the needs of the agroecosystem to the total area of crop rotation:

$$\frac{S_{CBE}}{S_{CR}} = \frac{\alpha_G\gamma_G}{\left(Y_W k_{WS} k_{BEW} + Y_B k_{BS} k_{BEB} + Y_C k_{CS} k_{BEC}\right)\gamma_{BE}} \quad (7)$$

where: S_{CBE} - the area under wheat, barley and corn at the same value required to produce bioethanol for the needs of the agroecosystem, ha.

If the production of bioethanol is carried out only based on wheat, barley, or corn, the ratio of the area under these crops for the production of bioethanol for the needs of the agroecosystem to the total area of crop rotation will be:

$$\frac{S_W}{S_{CR}} = \frac{\alpha_G\gamma_G}{Y_W k_{WS} k_{BEW}\gamma_{BE}};\ \frac{S_B}{S_{CR}} = \frac{\alpha_G\gamma_G}{Y_B k_{BS} k_{BEB}\gamma_{BE}};\ \frac{S_K}{S_C} = \frac{\alpha_G\gamma_G}{Y_C k_{CS} k_{BEC}\gamma_{BE}} \quad (8)$$

The graphic dependence of the ratio of the area under wheat, barley and corn at the same value required to produce bioethanol for the needs of the agroecosystem to the total area of crop rotation from the typical needs of the agroecosystem in gasoline is shown in Figure 5 for clarity.

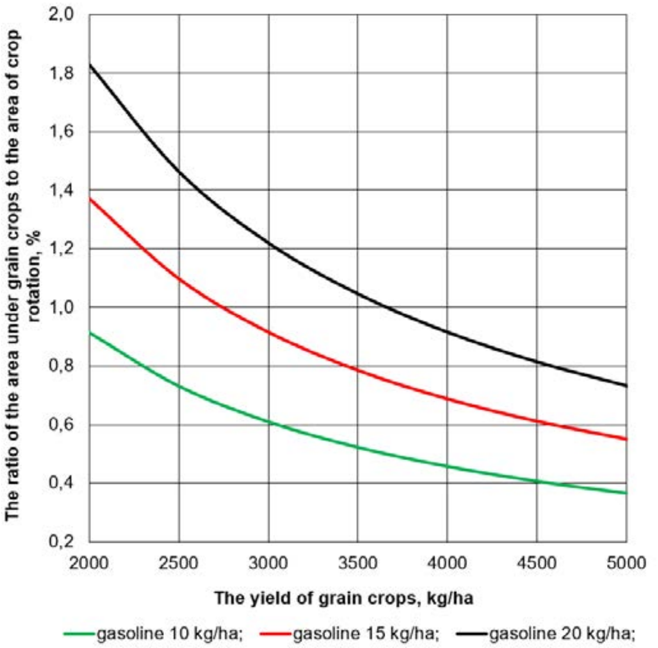

Figure 5. Dependence of the ratio of the area under wheat, barley and corn at their equal value, necessary for the production of bioethanol for the needs of the agroecosystem to the total area of crop rotation on the typical needs of the agroecosystem for gasoline and the yield of grain crops

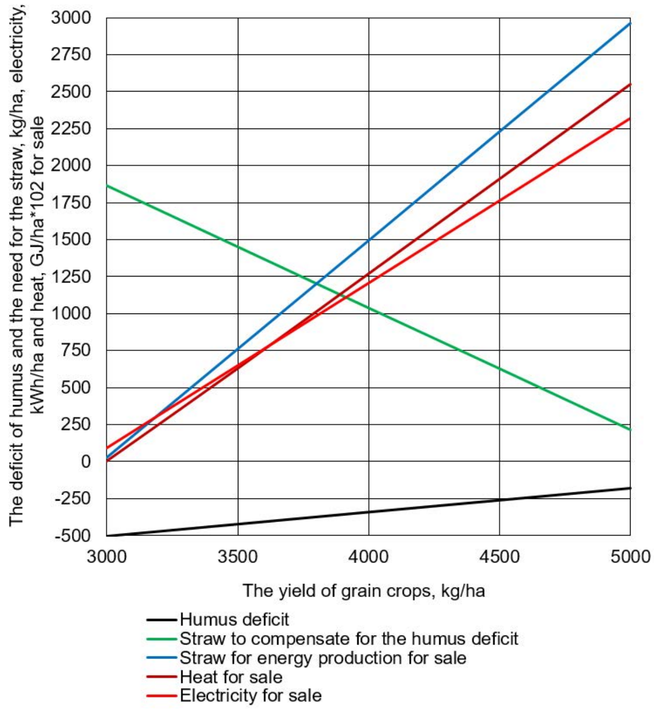

Figure 6. Dependence of the humus deficit, the need for straw to compensate for the loss of humus, the amount of straw for energy production for sale, as well as the volume of electricity and heat for sale on the average yield of grain crops

Thus, with the average typical demand of the agroecosystem for gasoline from 15 to 16 kg/ha, the ratio of the area under wheat, barley and corn at the same value required to produce bioethanol for the needs of the agroecosystem to the total area of crop rotation with a grain yield of 3000 to 4000 kg/ha is from 0.7 to 0.9%. This means that to cover the needs of the agroecosystem in bioethanol, no more than 1% of the crop rotation area under grain crops is needed.

The results of calculating the volume of electricity and heat for sale to other consumers based on the resources of plant biomass of agroecosystem are shown in Figure 6.

The analysis showed that the production of heat and electricity is largely determined by the yield of grain crops. An increase in the yield of grain crops from 3000 to 5000 kg/ha causes an increase in the intake of organic matter into the soil to a greater extent than its mineralization, and accordingly the deficit of organic matter and humus decreases from 507 to 180 kg/ha.

When the yield of grain crops increases from 3000 to 5000 kg/ha, the volume of plant biomass (mainly straw) to compensate for the lack of organic matter and humus decreases from 1867 to 217 kg/ha. This leads to an increase in the possible volumes of plant biomass for energy production for sale from 27 to 2963 kg/ha, and, accordingly, the production of electricity from 48 to 2301 kWh/ha and heat from 0 to 25.5 GJ/ha, while meeting their own needs for heat and electricity by burning biogas in a cogeneration plant. The main component of the agroecosystem, which allows ensuring its energy autonomy, is an installation consisting of a gas generator and an electric generator (gas generator cogeneration unit) (Perez et al., 2015; Jankowski, 2020). The basic element of a cogeneration gas generator plant is a gas generator that operates on straw pellets. To demonstrate the possibilities of obtaining heat and electricity from straw, it is advisable to consider a specific calculation example (Table 3), which specifies one of the points in the graph shown in Figure 6 at an average grain yield of 3800 kg/ha.

Of particular interest is also the distribution of the energy equivalent of plant biomass (mainly straw) per hectare (Figure 7) with an average grain yield of 3800 kg/ha.

Table 3. Example of calculating the production capacity for the sale of heat and electricity from straw per hectare

Indicator	Value
Total amount of straw produced in the agroecosystem, St_{CR}	3258 kg
The amount of plant biomass in the form of grain waste, which is the waste of grain cleaning, *GW*	47 kg
Total plant biomass, St_{CR}+ *GW*	3305 kg
The amount of straw that is lost during harvesting of the crop rotation, St_L	266 kg
The amount of plant biomass that remains in crop rotation fields to compensate for the loss of humus in the form of crushed corn residues, BM_{CH}	598 kg
St_{CR} The amount of straw that is used for the production of mushroom products, St_{MP}	33 kg
Additional amount of straw that is used to compensate for the loss of humus in the crop rotation, St_{AH}	1207 kg
The amount of plant biomass that can be used in the agroecosystem for the production of briquettes and pellets and the subsequent production of heat and electricity using a gas generator for sale, St_E=St_{GG}	1201 kg
The amount of electrical energy generated by a gas generator for sale, Q^{EE}_{StBP},	1010 kWh
The amount of heat generated by a gas generator for sale, Q^{TE}_{StBP}	10 GJ

Of particular interest is the distribution of the energy equivalent of plant biomass (mainly straw) with an average grain yield of 3800 kg/ha (Figure 7). This distribution demonstrates that, in terms of energy equivalents, 63% of plant biomass is used for maintaining the humus balance in the crop rotation. Most of this biomass was contributed by straw that was composted and subsequently applied to fields (36%), followed by crushed corn residues (18%) and straw that is lost during harvest (8%).

The energy equivalent of plant biomass that can be used to produce heat and electricity for sale is 37%, including losses in energy production of 7%.

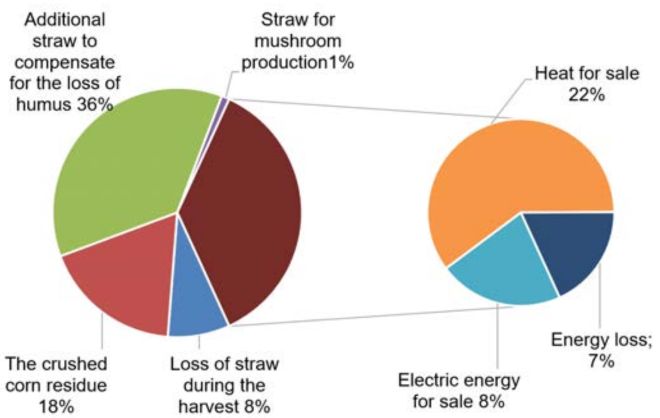

Figure 7. Distribution of the energy equivalent of plant biomass with an average grain yield of 3800 kg/ha

It should be noted that the amount of straw to compensate for the loss of humus largely depends on the yield of cereals in crop rotation. With increasing grain yields in crop rotation, the amount of biomass to compensate for the loss of humus can be reduced. When the grain yield increases from 3000 to 5000 kg/ha, the relative amount of biomass to compensate for humus losses can be reduced from 99 to 32% of the total biomass. With the structure of crop rotation and yield, that has developed in Ukraine, the average value of the relative amount of biomass that must be directed to compensate for the loss of humus is about 70%.

The conducted research (Golub et al., 2018) allowed us to conclude that straw pellets are suitable as a fuel for generating gas. However, when the gas generator is running on fuel with a content of straw pellets of 40% or more, the formation of solid glassy deposits on the surface of the grate of the gas generator was observed.

The use of fuel with a straw pellet content of more than 40% required the development of gas generator designs that will avoid the formation of persistent deposits on the working surfaces. This study was carried out by the authors of this paper (Golub et al., 2020b) which ensures not only full energy autonomy of agroecosystem, but also the possibility of supplying of the excess electricity and heat to third-party consumers.

CONCLUSIONS

The study of indicators of agroecosystem without external energy supply allows us to provide compensation for the needs of the agroecosystem in liquid fuel, heat, and electricity at the expense of plant biomass. Based on the analysis of the energy balance of agroecosystem, we calculated the ratio of the area under rapeseed needed to produce biodiesel and the area under wheat, barley and corn necessary for the production of bioethanol for the needs of agroecosystem to the total area of crop rotation. An additional amount of straw was calculated to compensate for the loss of humus in crop rotation, which makes it possible to determine the amount of plant biomass that can be used for heat and electricity generation using a cogeneration gas generator plant. The volumes of plant biomass that can be used for excess production of heat and electricity for their sale to third-party consumers have been determined.

It was also found that at the average typical needs of the agroecosystem in diesel fuel from 60 to 80 kg/ha, the ratio of the area under rapeseed needed for biodiesel production for the needs of agroecosystem of total area of crop rotation with grain yield of rapeseed from 1500 to 2500 kg/ha is from 8.3 to 18.5%, or in average from 10.4 to 13.9%, which is less than the area of one field in a six-field crop rotation. With the average typical demand of the agroecosystem for gasoline from 15 to 16 kg/ha, the ratio of the area under wheat, barley and corn at the same value required to produce bioethanol for the needs of the agroecosystem to the total area of crop rotation with a crop yield of 3000 to 4000 kg/ha is from 0.7 to 0.9%.

The volume of production of heat and electric energy using a cogeneration gas generator plant is largely determined by the yield of grain crops. The increase in grain yield from 3000 to 5000 kg/ha causes an increase in the supply of organic matter to the soil to a greater extent than its mineralization, and accordingly the deficit of organic matter and humus is reduced from 507 to 180 kg/ha, the volume of plant biomass (mainly straw) to compensate for the deficit of organic matter and humus is reduced from 1867 to 217 kg/ha, which causes an increase in the possible volumes of plant biomass for energy production for sale from 27 to 2963 kg/ha, and respectively, electricity production from 48 to 2301 kWh/ha and heat from 0 to 25,5 GJ/ha, when providing their own needs for heat and electricity by burning biogas in a cogeneration plant.

REFERENCES

Araujo Enciso, S., Fellmann, T., Pérez Dominguez, I., Santini, F. (2016) Abolishing biofuel policies: Possible impacts on agricultural price levels, price variability and global food security. Food Policy, 61, 9–26. DOI: https://doi.org/10.1016/j.foodpol.2016.01.007

Belcher, K., Boehm, M., Fulton, M. (2004) Agroecosystem sustainability: a system simulation model approach. Agricultural Systems, 79 (2), 225-241. DOI: https://doi.org/10.1016/S0308-521X(03)00072-6

Çakan, A., Kiren, B., Duran, F., Çınar, B., Ayas, N. (2019) Evaluation of Sugar Beet Waste in the Production of Hydrogen-Rich Gas. International Journal of Renewable Energy Research, 9 (3), 1214-1223. Available at: https://www.ijrer.org/ijrer/index.php/ijrer/article/view/9494/pdf

Carlucci, I., Mutani, G., Martino, M. (2015) Assessment of potential energy producible from agricultural biomass in the municipalities of the Novara plain. International Conference on Renewable Energy Research and Applications (ICRERA), Palermo. 22- 25 Novembe 2015, pp. 1394-1398.

Conway, G. (1987) The properties of agroecosystems. Agricultural Systems, 24 (2), 95-117. DOI: https://doi.org/10.1016/0308-521X(87)90056-4

Fore, S. R., Porter, P., Lazarus, W. (2011) Net energy balance of small-scale on-farm biodiesel production from canola and soybean. Biomass and Bioenergy, 35 (5), 2234–2244. DOI: https://doi.org/10.1016/j.biombioe.2011.02.037

Fredriksson, H., Baky, A., Bernesson, S., Nordberg, A., Norén, O., Hansson, P.-A. (2006) Use of on-farm produced biofuels on organic farms – Evaluation of energy balances and environmental loads for three possible fuels. Agricultural Systems, 89 (1), 184–203. DOI: https://doi.org/10.1016/j.agsy.2005.08.009

Golub, G. Skydan, O., Kukharets, V., Yarosh, Y., Kukharets, S. (2020a) The estimation of energetically self-sufficient agroecosystem's model. Journal of Central European Agriculture, 21 (1), 168-175. DOI: https://doi.org/10.5513/JCEA01/21.1.2482

Golub, G., Kukharets, S., Skydan, O., Yarosh, Y., Chuba, V., Golub, V. (2020b) The optimization of the gasifier recovery zone height when working on straw pellets. International Journal of Renewable Energy Research, 10 (2), 529-536.

Golub, G., Kukharets, S., Yarosh, Y., Kukharets, V. (2017) Integrated use of bioenergy conversion technologies in agroecosystems. INMATEH – Agricultural Engineering, 51 (1), 93–100.

Golub, G., Kukharets, S., Tsyvenkova, N., Yarosh, Ya., Chuba, V. (2018) Experimental study into the influence of straw content in fuel on parameters of generator gas. Eastern-European Journal of Enterprise Technologies, 5 (95), 76-86. DOI: https://doi.org/10.15587/1729-4061.2018.142159

Harrouz, A., Abbes, M., Colak, I., Kayisli, K. (2017) Smart grid and renewable energy in Algeria. IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA). San Diego, 5-8 Novembe 2017, pp. 1166-1171.

Jankowski, K., Dubis, B., Sokólski, M., Załuski, D., Bórawski, P., Szempliński, W. (2020) Productivity and energy balance of maize and sorghum grown for biogas in a large-area farm in Poland: An 11-year field experiment. Industrial Crops and Products, vol. 148, 112326. DOI: https://doi.org/10.1016/j.indcrop.2020.112326

Javed, Z. H., Shabir, M., Ria, M. (2018) Agricultural Productivity and CO2 Emission in Pakistan: An Econometric Analysis. International Journal of Renewable Energy Research, 8 (3), 1535-1543.

Kang, S., Wang, D., Nichols, J., Schuchart, J., Kline, K., Wei, Y., Izaurralde, R. (2015) Development of mpi_EPIC model for global agroecosystem modeling. Computers and Electronics in Agriculture, 111, 48–54. DOI: https://doi.org/10.1016/j.compag.2014.12.004

Koizumi, T. (2013) Biofuel and food security in China and Japan. Renewable and Sustainable Energy Reviews, 21, 102–109. DOI: https://doi.org/10.1016/j.rser.2012.12.047

Matin, A., Majdak, T., Krička, T., Grubor, M. (2018) Valorization of sunflower husk after seeds convection drying for solid fuel production. Journal of Central European Agriculture, 20 (1), 389-401. DOI: https://doi.org/10.5513/JCEA01/20.1.2018

Melece, L., Krieviņa, A. (2016) Bioenergy in Latvia: sector value and impacts. Proceedings 15th International Scientific Conference Engineering for rural development Proceedings, Elgava, 15, pp. 1170-1176.

Mockshell, J., Villarino, Ma. E. (2019) Agroecological intensification: Potential and limitations to achieving food security and sustainability. Encyclopedia of Food Security and Sustainability, 3, 64–70. DOI: https://doi.org/10.1016/B978-0-08-100596-5.22211-7

Moonen, A.-C., Bàrberi, P. (2008) Functional biodiversity: An agroecosystem approach. Agriculture. Ecosystems & Environment, 127 (1–2), 7-21. DOI: https://doi.org/10.1016/j.agee.2008.02.013

Orynycz, O. (2017) Influence of tillage technology on the energy efficiency of a rapeseed plantation. Procedia Engineering, 182, 532–539. DOI: https://doi.org/10.1016/j.proeng.2017.03.148

Pérez, N., Machin, E., Pedroso, D., Roberts, J., Antunes, J., Silveira, J. Biomass (2015) Gasification for Combined Heat and Power Generation in the Cuban Context: Energetic and Economic Analysis. Applied Thermal Engineering, 90, 1-12. DOI: https://doi.org/10.1016/j.applthermaleng.2015.06.095 1359-4311

Prasad, S., Singh, A., Korres, N., Rathore, D., Sevda, S., Pant, D. (2020) Sustainable utilization of crop residues for energy generation: A Life Cycle Assessment (LCA) perspective. Bioresource Technology, vol. 303. 122964. DOI: https://doi.org/10.1016/j.biortech.2020.122964

Preston, B., King, A., Ernst, K., Absar, S., Nair, S., Parish, E. (2015) Scale and the representation of human agency in the modeling of agroecosystems. Current Opinion in Environmental Sustainability, 14, 239–249. DOI: https://doi.org/10.1016/j.cosust.2015.05.010

Rodias, E., Lampridi, M., Sopegno, A., Berruto, R., Banias, G., Bochtis, D., Busato, P. (2019) Optimal energy performance on allocating energy crops. Biosystems Engineering, 181, 11–27. DOI: https://doi.org/10.1016/j.biosystemseng.2019.02.007

Ryabchenko, O., Golub, G., Turčeková, N., Adamičková, I., Zapototskyi, S. (2017) Sustainable business modeling of circular agriculture production: case study of circular bioeconomy. Journal of Security and Sustainability, 7 (2), 301-309. DOI: https://doi.org/10.9770/jssi.2017.7.2(10)

Sami, M., Shiekhdavoodi, M., Almassi, M., Marzban, A. (2013) Assessing the sustainability of agricultural production systems using fuzzy logic. Journal of Central European Agriculture, 14 (3), 171-1183. DOI: https://doi.org/10.5513/JCEA01/14.3.1323

Siegmeier, T., Blumenstein, B., Möller, D. (2019) Bioenergy Production and Organic Agriculture. Organic farming. Global perspectives and methods, C. 11, pp. 331–359, 2019, DOI: https://doi.org/10.1016/B978-0-12-813272-2.00012-4

Subramaniam, Y., Masron, T., Azman, N. (2019) The impact of biofuel on food security. International Economics, 160, 72-83. DOI: https://doi.org/10.1016/j.inteco.2019.10.003

Verdade, L., Piña, C., Rosalino, L. (2015) Biofuels and biodiversity: Challenges and opportunities. Environmental Development, 15, 64–78. DOI: https://doi.org/10.1016/j.envdev.2015.05.003

Wasiak, A. (2017) Effect of Biofuel Production on Sustainability of Agriculture. Procedia Engineering, 182, 739–746. DOI: https://doi.org/10.1016/j.proeng.2017.03.192

Yakubiv, V., Boryshkevych, I., Piatnychuk, I., Iwaszczuk, N., Iwaszczu, A. (2020) Strategy for the Development of Bioenergy Based on Agriculture: Case for Ukraine. International Journal of Renewable Energy Research, 10 (3), 1092-1102.