Researching of indicators of agroecosystem without external energy supply

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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).
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).

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:

\[
Q_{D} = Q_{G} + \sum_{i=1}^{n} Q_{i}^{E} - Q_{BG} + Q_{DBF} + Q_{BE} + Q_{St}\]

(1)

where

- \( Q_{D} \) - energy equivalent of the typical agroecosystem demand for diesel and gasoline, MJ;
- \( Q_{G} \) - energy equivalent of diesel biofuels and bioethanol produced for the needs of the agroecosystem, MJ;
- \( \sum_{i=1}^{n} Q_{i}^{E} \) - the total demand of all technological processes in the agroecosystem for heat and electricity, MJ;
- \( Q_{BG}, Q_{DBF}, Q_{BE} \) - production of heat and electricity from biogas, diesel biofuels and straw briquettes and pellets, MJ;
- \( Q_{St}^{E} \) - 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:

\[
St_{e} = St_{cr} + GW - St_{L} - BM_{CH} - St_{LP} + St_{LC} - St_{MP} - St_{AH} \]

(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:

\[
D_{H} = H_{PB} - M_{HCR} + \sum_{i=1}^{m} H_{j} \left(1 - \frac{W_{i}}{100}\right) k_{hi} + St_{AP} \left(1 - \frac{W_{s}}{100}\right) k_{HS} = 0
\]

(3)

where

- \( D_{H} \) - the deficit of humus in crop rotation, t;
- \( H_{PB} \) - 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;
- \( W_{i}, W_{s} \) - relative humidity of plant biomass entering the fields (plant biomass of siderates, weeds, compost and waste substrate after growing mushrooms), as well as straw, %;
- \( k_{hi}, k_{HS} \) - 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:
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

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>The energy equivalent of the typical agroecosystem demand for diesel fuel</td>
<td>( Q_{DF} = \alpha_{DF} S_{CR} \gamma_{DF} )</td>
</tr>
<tr>
<td>( Q_{DF} ) – typical demand of the agroecosystem for diesel fuel, kg/ha; ( S_{CR} ) – total area of crop rotation, ha; ( \gamma_{DF} ) – calorific value of diesel fuel, MJ/kg</td>
<td></td>
</tr>
<tr>
<td>Energy equivalent of diesel biofuel produced for the needs of the agroecosystem</td>
<td>( Q_{DBF} = m_{RS} k_{O} k_{DBF} \gamma_{DBF} = Y_{R} k_{O} S_{RS} k_{DBF} \gamma_{DBF} )</td>
</tr>
<tr>
<td>( 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.; ( \gamma_{DBF} ) – calorific value of diesel biofuel, MJ/kg; ( Y_{R} ) – the yield of rapeseed, kg/ha; ( S_{RS} ) – the area under rapeseed necessary for the production of diesel biofuels for the needs of the agroecosystem, ha</td>
<td></td>
</tr>
<tr>
<td>Energy equivalent of the typical agroecosystem demand for gasoline</td>
<td>( Q_{G} = \alpha_{G} S_{CR} \gamma_{G} )</td>
</tr>
<tr>
<td>( \alpha_{G} ) – typical agroecosystem demand for gasoline, kg/ha; ( \gamma_{G} ) – calorific value of gasoline, MJ/kg</td>
<td></td>
</tr>
<tr>
<td>Energy equivalent of bioethanol produced for the needs of the agroecosystem</td>
<td>( Q_{BE} = \left( Y_{W} k_{EB} k_{BEW} + Y_{B} k_{EB} k_{BEB} + Y_{C} k_{EB} k_{BEC} \right) \gamma_{BE} )</td>
</tr>
<tr>
<td>( k_{EB}, k_{BEW}, k_{BEB}, k_{BEC} ) – the coefficients of the output of bioethanol from wheat, barley and corn, rel. un.; ( \gamma_{BE} ) – calorific value of bioethanol, MJ/kg; ( Y_{W}, Y_{B}, Y_{C} ) – wheat, barley and corn yields, kg/ha; ( k_{W}, k_{B}, k_{C} ) – 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</td>
<td></td>
</tr>
<tr>
<td>Total demand of all technological processes of the agroecosystem for heat energy</td>
<td>( \sum_{i=1}^{n} Q_{TEi} = \sum_{i=1}^{n} Y_{TEi} P_{i} )</td>
</tr>
<tr>
<td>( Y_{TEi} ) – the specific thermal energy demand, MJ/thous. un. in egg production, MJ/m³ 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, m³ in biogas production, t in the production of other products</td>
<td></td>
</tr>
<tr>
<td>Total demand of all technological processes of the agroecosystem for electricity</td>
<td>( \sum_{i=1}^{n} Q_{EEi} = \sum_{i=1}^{n} Y_{EEi} P_{i} )</td>
</tr>
<tr>
<td>( Y_{EEi} ) – specific electricity demand, MJ/thous. un. in egg production, MJ/m³ in biogas production, MJ/t in the production of other products</td>
<td></td>
</tr>
<tr>
<td>Production of heat and electricity from biogas</td>
<td>( Q_{TE} = V_{BG} k_{M} k_{E} (1 - k_{TE}^{*}) )</td>
</tr>
<tr>
<td>( Q_{EE} = V_{BG} k_{M} k_{E} (1 - k_{EE}^{*}) )</td>
<td></td>
</tr>
<tr>
<td>( V_{BG} ) – the biogas yield, m³; ( k_{M} ) – methane content in biogas, rel. un.; ( \gamma_{M} ) – heat of methane combustion, MJ/m³; ( k_{TE}^{<em>}, k_{EE}^{</em>} ) – relative output of heat and electricity when running a biogas cogenerator, rel. un.; ( k_{TE}^{<em>}, k_{EE}^{</em>} ) – relative consumption of heat and electricity for own needs, rel. un.</td>
<td></td>
</tr>
<tr>
<td>The production of heat and electric power from biodiesel</td>
<td>( Q_{TE}^{T} = M_{DBF} \gamma_{DBF} )</td>
</tr>
<tr>
<td>( Q_{EE}^{T} = M_{DBF} \gamma_{DBF} )</td>
<td></td>
</tr>
<tr>
<td>( M_{DBF} ) – the amount of diesel biofuels for heat and electricity generation, kg; ( \gamma_{DBF} ) – relative output of heat and electricity when running a cogenerator on diesel biofuel, rel. un.</td>
<td></td>
</tr>
<tr>
<td>Production of heat energy from baled straw</td>
<td>( Q_{H} = S_{TE} Y_{g} )</td>
</tr>
<tr>
<td>( S_{TE} ) – volume of baled straw to compensate for the thermal needs of the agroecosystem, t; ( Y_{g} ) – heat of straw combustion, MJ/t; ( \eta_{B} ) – efficiency of the boiler for burning plant biomass, rel. un.</td>
<td></td>
</tr>
<tr>
<td>Production of heat and electricity from straw briquettes and pellets using a gas generator</td>
<td>( Q_{TE}^{g} = S_{TE} Y_{g} \gamma_{g} )</td>
</tr>
<tr>
<td>( Q_{EE}^{g} = S_{TE} Y_{g} \gamma_{g} )</td>
<td></td>
</tr>
<tr>
<td>( S_{TE} ) – volume of baled straw to compensate for the thermal needs of the agroecosystem, t; ( Y_{g} ) – heat of straw combustion, MJ/t; ( \gamma_{g} ) – calorific value of straw, MJ/kg; ( \eta_{B} ) – efficiency of the boiler for burning plant biomass, rel. un.</td>
<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total amount of straw produced in the agroecosystem</td>
<td>( St_{CR} = Y_{WS} k_{StW} + Y_{BS} k_{StB} + Y_{CS} k_{StC} + Y_{RS} k_{StR} )</td>
</tr>
<tr>
<td>( 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.</td>
<td></td>
</tr>
<tr>
<td>The amount of plant biomass in the form of grain waste, which is the waste of grain cleaning</td>
<td>( GW = (Y_{WS} + Y_{BS} + Y_{CS} + Y_{RS}) k_{GW} )</td>
</tr>
<tr>
<td>( 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.</td>
<td></td>
</tr>
<tr>
<td>The amount of straw that is lost during harvesting of the crop rotation</td>
<td>( St_{L} = (Y_{WS} + Y_{BS} + Y_{CS} + Y_{RS}) k_{StL} )</td>
</tr>
<tr>
<td>( k_{StL} ) - the coefficient of straw loss on stubble and during harvest in relation to the biological straw yield, rel. un.</td>
<td></td>
</tr>
<tr>
<td>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</td>
<td>( BM_{CH} = Y_{CS} k_{StC} )</td>
</tr>
<tr>
<td>The amount of straw that is used for bedding in pig farming</td>
<td>( St_{LP} = \tau_{LP} q_{LP} n_{P} )</td>
</tr>
<tr>
<td>( q_{LP} ) - specific consumption of straw for litter for pigs, t/(un. day); ( n_{P} ) - average annual number of pigs, un.; ( \tau_{LP} ) - number of days of litter used for pigs</td>
<td></td>
</tr>
<tr>
<td>The amount of straw used for bedding in dairy farming</td>
<td>( St_{LC} = \tau_{LC} q_{LC} n_{C} )</td>
</tr>
<tr>
<td>( q_{LC} ) - specific consumption of straw for bedding for cows, t/(un. day); ( n_{C} ) - average annual number of cows, un.; ( \tau_{LC} ) - number of days of litter used for cows</td>
<td></td>
</tr>
<tr>
<td>The amount of straw that is used for the production of mushroom products</td>
<td>( St_{LC} ) - is determined by the volume of mushroom production</td>
</tr>
</tbody>
</table>

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.

Thus, taking into account the above dependencies, the overall energy balance of an agroecosystem will have the following form:
For an agroecosystem without livestock production, this system is somewhat simplified due to the absence of indicators such as production of heat \( M_{\text{DEF}}/\text{DEF}_{\text{P}} = 0 \) and electric energy \( M_{\text{DEF}}/\text{DEF}_{\text{E}} = 0 \) from diesel biofuels and the lack of need to spend straw on bedding in pig and dairy farming. In addition, in this agroecosystem there is no need to spend baled straw for heat needs \( St_{\text{TE}} = 0 \), 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 \( St_{\text{CR}} \); 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 \( St_{\text{L}} \); the amount of plant biomass that remains in crop rotation fields to compensate for the loss of humus \( BM_{\text{CH}} \); the amount of straw that is used for the production of mushroom products \( St_{\text{MP}} \) and according to the equation (4) an additional amount of straw that remains to compensate for the loss of humus in the crop rotation \( St_{\text{AH}} \). 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 \( St_{\text{E}} \).

In general, the volume of electricity and heat for sale to other consumers was determined based on the resources of plant biomass of agroecosystem.
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:

\[ \frac{S_{CR}}{S_{CR}} \cdot \frac{\alpha_{DF}}{\alpha_{DF}} \cdot \frac{\gamma_{DF}}{\gamma_{DF}} \quad (6) \]

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 to the total area of crop rotation on the yield of rapeseed and typical need of the agroecosystem in diesel fuel

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:

\[ \frac{S_{CR}}{S_{CR}} \cdot \frac{\alpha_{G}}{\alpha_{G}} \cdot \frac{\gamma_{BE}}{\gamma_{BE}} \quad (7) \]

where:

\[ SC_{BE} \] - 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:

\[ \frac{S_{W}}{S_{CR}} = \frac{\alpha_{G}}{\alpha_{G}} \cdot \frac{\gamma_{BE}}{\gamma_{BE}} \quad (8) \]

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.

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.

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.

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. 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

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total amount of straw produced in the agroecosystem, ( \text{St}_{\text{CR}} )</td>
<td>3258 kg</td>
</tr>
<tr>
<td>The amount of plant biomass in the form of grain waste, which is the waste of grain cleaning, ( \text{GW} )</td>
<td>47 kg</td>
</tr>
<tr>
<td>Total plant biomass, ( \text{St}_{\text{CR}} ) + ( \text{GW} )</td>
<td>3305 kg</td>
</tr>
<tr>
<td>The amount of straw that is lost during harvesting of the crop rotation, ( \text{St}_{\text{L}} )</td>
<td>266 kg</td>
</tr>
<tr>
<td>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, ( \text{BM}_{\text{CH}} )</td>
<td>598 kg</td>
</tr>
<tr>
<td>( \text{St}_{\text{MP}} ), The amount of straw that is used for the production of mushroom products</td>
<td>33 kg</td>
</tr>
<tr>
<td>Additional amount of straw that is used to compensate for the loss of humus in the crop rotation, ( \text{St}_{\text{AH}} )</td>
<td>1207 kg</td>
</tr>
<tr>
<td>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, ( \text{St}<em>{\text{E}} = \text{St}</em>{\text{GG}} )</td>
<td>1201 kg</td>
</tr>
<tr>
<td>The amount of electrical energy generated by a gas generator for sale, ( \text{Q}_{\text{E}}^{\text{FE}} )</td>
<td>1010 kWh</td>
</tr>
<tr>
<td>The amount of heat generated by a gas generator for sale, ( \text{Q}_{\text{E}}^{\text{HE}} )</td>
<td>10 GJ</td>
</tr>
</tbody>
</table>

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%.

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


