



Simulation Model for Biogas Project Efficiency Maximization

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Abstract

A simulation method (SM), linear programming method (LPM), project evaluation methods (PEMs), and whole farm modeling (WFM) were applied to analyze the investment appeal of a biogas project on a Russian farm. The biogas project was evaluated for constant input parameters. The project efficiency evaluation procedure was elaborated to evaluate and maximize biogas investment project efficiency. The procedure to evaluate the project efficiency includes defining the optimal state of the farm for the situations “with project” and “without project.” The main elements for optimization are the equipment for anaerobic digestion, substrate blend structure, fertilizing plan, cost plan, and farm production structure. The optimization was fulfilled by simulation modeling (SM) and LPM. The situations “with project” and “without project” were compared by using PEMs, the main indicators of project efficiency: net present value (NPV), internal rate of return (IRR), payback period (PBP), and profitability index (PI). The optimal substrate blend structure was defined by the direct search method (DSM) to select the probe providing the highest NPV afterward. The procedure to maximize biogas project efficiency was applied to justify the benefits of biogas production on the farm under corresponding conditions and to work out the recommendations for businesses and municipalities.

Keywords Anaerobic digestion · Linear programming method · Project evaluation methods · Scenario analysis · Russia

Abbreviations

AD	Anaerobic digestion
BGP	Biogas plant
CHPP	Combined heat and power plant
DSM	Direct search method
EEP	Efficiency evaluation procedure
FSSS	Federal State Statistical Service
IRR	Internal rate of return
FPO	Fertilizing plan optimization
FPPO	Farm production plan optimization
LP	Linear programming

LPM	Linear programming modeling
NPV	Net present value
PBP	Payback period
PEM	Project evaluation methods
PI	Profitability index
SM	Simulation model/modeling
CPO	Cost plan optimization
SBO	Substrate blend optimization
WFM	Whole farm modeling

Introduction

The Russian Federation is one of the largest oil and natural gas exporters. At the same time, it has a huge potential for the development of renewable energy technologies. Although the Russian government approved numerous statutes regulating the energy production sector [1–12], renewable energy is still neglected, not developed, and is not a supported industry in the country [13]. Biogas and other renewables are not considered and accounted for by the Russian’s main statistical service, Federal State Statistical Service (FSSS), as a full-value energy source. The electricity production structure is only presented by thermal, hydro, and

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nuclear energy. The interest in the biogas industry is low due to the dominance of the hydrocarbon economy and a policy oriented toward the fossil fuel production of the country.

The biogas production industry in Russia will only develop if potential producers of biomass (mainly farms) are convinced of the economic viability of biogas production. Efficiency evaluation, in turn, is based on the investment appeal of applying anaerobic digestion (AD) technology on a farm.

Biogas production on a farm requires installing a biogas plant (BGP) and certain resources on the farm for an optimal BGP operation. Integration of biogas production technology into the farm production system always causes changes in the production structure of the farm. Field management, crop rotation, fertilizing plan, livestock system, primary and secondary production structure, cash flows, and other elements will have significant shifts in their structures. Various natural, economic, technical, and social factors influence the project. Therefore, identifying and analyzing these changes is required, and planning of the future production process is needed.

These problems can be successfully solved by means of SM, LP, PEMs, and WFM. The combination of these instruments permits the evaluation of the investment appeal of BGP implemented on a farm and is strongly based on a holistic quantitative approach and mathematical modeling. They provide an opportunity to balance and plan all the involved sectors of the farm.

In the context of changing market conditions, the farm has various problems that cause issues for long-term forecasting. On the one hand, a short-term crop rotation plan, reducing subsidies for animal production, and the unprofitability of this sector require the farm to look for new ways to stay profitable by means of restructuring the whole farm production structure. Worldwide experience considers biogas production on farms as a favorable solution to improve the structure of agricultural production. However, in Russia, this question is rather complicated because of the existing legislation, which is not oriented to realizing ideas to produce electricity and sell it to the common net. In this study, we assume the best scenario regarding the political conditions to use it as a possible recommendation for the government in the future. At the same time, biogas production requires purchasing and the installation of BGPs and CHPPs as well as changing the infrastructure for biogas production (e.g., the building of storage for substrates and fertilizers) with corresponding capital costs. Therefore, it is highly suitable to evaluate the investment appeal of biogas production as a project (here: investment project) to be analyzed by means of PEM.

This evaluation uses benefit/cost analysis, and it is based on the comparative analysis of two states of the system (here: farm): “with project” and “without project”

(here: “with biogas production” and “without biogas production”). According to the methodology, capital costs are added to operational costs in corresponding years of the project. If the project is implemented on a real functioning farm, its influence and efficiency are to be defined on the basis of incremental cash flows of costs and revenue, i.e., result parameters are to be defined when comparing situations “with project” and “without project” rather than “before project” and “after project” or ignoring the situation “without project” at all [14].

Over and above the necessity to compare situations “with project” and “without project,” the importance of the description and prognosis of the situation “without project” should be pointed out with the same accuracy as the description and prognosis of the situation “with project”. An economic evaluation of the project is based on the common evaluation criteria: net present value (NPV), internal rate of return (IRR), payback period (PBP), and profitability index (PI).

The modeling of biogas production on a farm is a developing field of study: recent research generally widely uses modeling to optimize biogas production on a farm and to justify separate elements (e.g., tariffs) of the biogas production system in particular.

Among others, Yılmaz Balaman and Selim elaborated on the decision support system for the design and management of anaerobic digestion-based biomass to energy supply chains in a cost-effective and environment-friendly manner by inherent uncertainties [15]. The proposed model is solved by using different fuzzy goal programming approaches. This decision support system is based on a fuzzy multiobjective mixed-integer linear programming model. The research, in particular, revealed that payback periods of the biomass to energy supply chain configuration options obtained by different solution approaches change between 5 and 8 years, which is important considering the fact that the payback period of such systems usually varies from 3 to 15 years in real-world implementations. [15].

Jones and Salter described the integration of biogas production into a farm structure by WFM by means of LP [16]. Jones and Salter in their work showed a whole-farm, optimization modeling approach to determine the viability of AD in a more holistic way, taking into account such factors as AD scale, synergies and conflicts with other farm enterprises, choice of feedstocks, digestate use, and impact on farm net margin. In particular, the model showed that AD is complementary to dairy enterprises, but competes with arable enterprises for farm resources. Also, from the results of modeling, it was concluded that reduced nutrient purchases significantly improve the net margin on arable farms but the AD scale is constrained by the capacity of farmland to absorb nutrients in AD digestate [16].

Linear programming optimization method was applied to propose the blending strategy by García-Gen et al. [17]. The method combines experimental and heuristic information to define the objective function and the linear restrictions, to maximize chemical oxygen demand (COD) conversion into methane with maintaining a digestate and biogas quality. The results were validated in a continuously operated plant, treating for several months different mixtures of such co-substrates as glycerin, gelatin and pig manure at a corresponding organic loading rates and hydraulic retention times between 32 and 40 days at mesophilic conditions. The method uses typically available experimental and heuristic data and can be directly applied in existing co-digestion plants to optimize feedings to maximize the methane production, which makes this approach an important forecaster to early assess the feasibility of different substrates blends under co-digestion [17].

Siegmeier et al. present the analysis of a combined system of organic farming and biomass energy production within WFM [18]. Multiple agronomic effects caused by anaerobic digestion of residue and waste biomass in organic agriculture were investigated and presented within a conceptual diagrammatic model of a single farm. Nitrogen dynamics, crop yield, product quality, crop rotations, weeds, plant health, and soil fertility were analyzed as the main parameters of the farm. The results of the system analysis showed that farm biogas production has the potential to increase overall nitrogen supply and nitrogen use efficiency and decrease labor and energy costs of the organic farm. System consequences of these effects include changes in farm productivity, stability, and resilience. Biogas integration into an organic farm may contribute to renewable energy supply without additional need for land, but with increasing food output and reducing greenhouse gas emissions from livestock manure, [18] it indicates possibilities for the eco-functional intensification of organic farming systems with solving the food–energy–climate problems.

Despite numerous Russian papers on mathematical modeling of agricultural production, information on biogas derived from agriculture, especially based on any kinds of modeling, is scarce in the Russian Federation. Those scientific works that include elements of SM, LP, PEMs, and WFM use them separately.

Among others, Druzyanova offered a technical and economic assessment of using biogas settings in the agrarian sector within available biogas projects in the Republic of Sakha (Yakutia) of the Russian Federation [19]. In this work, it was concluded that using biogas plants is definitely profitable and biogas production requires close attention from rural producers. The rural population, which will use a biogas plant, acquires a great potential for improving its socio-economic situation, and with appropriate optimization and intensification of production can achieve high results,

moving to a highly profitable level. In addition, the peculiarity of the implementation of energy-saving projects in the Republic of Sakha (Yakutia) is caused by the fact that the cost of energy carriers is significantly higher than in other regions of the Russian Federation by an average of 3 times. And the use of biogas plants allows making profit of two or three roubles for each invested rouble. Thus, the advantages of biogas technologies include independence from the state in the field of energy supply, saving money by switching to own biogas, producing energy and organic fertilizers instead of the usual disposal of organic waste, improving the ecology of an enterprise with biogas production, obtaining additional profit through the production of “green” energy, reducing the level of harmful emissions into the atmosphere, and creating additional economic support through energy production.

Lillepyarg elaborated the methodology of the energy potential defined for polygons of solid household waste [20]. Within this research, the analysis of the use of solid waste as renewable secondary energy resources was carried out, which showed the increasing role of this direction in energy-saving and reducing the environmental pollution. In this research, the expediency of collecting and disposing of biogas at landfills of solid waste in Russia has been revealed. An algorithm for automated construction of a geometric model of the landfill body has been developed and programmatically implemented, taking into account its parameters and the composition of household waste in any part of its volume. An automated software package has been developed and implemented to create a model of biogas emission and its distribution in space using laboratory experiment data and a geometric model of the landfill body, which allows calculating the potential of landfill biogas and methane content taking into account the conditions of waste disposal. Data on specific and total emissions of biogas and their composition were obtained based on the results of laboratory studies of waste buried at the Volkhonsky landfill. A geometric model of the body of the Volkhonsky landfill was created and calculations of the spatial distribution of the intensity of biogas emission were performed taking into account experimental data. The scheme of the energy complex as part of the biogas collection system, the diesel power plant that recycles landfill methane, and the wind power plant as an additional source of energy was developed. The energy output of a diesel power plant and a wind power plant is determined.

Organizational and economic features to realize biogas production potential in agriculture were investigated by Shahov for the Lipetsk region of the Russian Federation [21]. The results have shown the prerequisites for the production of pellets from straw and biogas production from animal waste for subsequent production of electrical and thermal energy in almost all municipal districts of the Lipetsk region within bioenergy systems. Among other

factors, the following ones were revealed as the prerequisites for biogas production in the region: the shortage of traditional fuels and energy, the increasing prices of energy, and (as a consequence) increasing prices of agricultural products, reserves of straw, and animal husbandry waste that agriculture of the region has as reserves. In addition, the organization of bioenergy production can provide additional jobs, which will help to reduce the unemployment rate in the region.

The challenge of evaluating the economic efficiency of applying the AD technology on a Russian farm appears to be a complex problem that can be solved by instruments of SM, LPM, WFM, and PEMs combining all numerous technical, technological, natural, social, and economic factors and conditions. To meet this challenge, the AD process was simulated for a real typical Russian farm producing animals and crops under constant parameters (like prices, crop yields, milk outputs, etc.) for each year of the project.

To simulate the biogas production on a farm and to maximize the benefits of the AD project, the project efficiency evaluation procedure was developed. This procedure includes optimizing the AD equipment, substrate blend structure, fertilizing plan, cost plan, and farm production plan in the situations “with project” and “without project” by using SM and LPM where needed. The situations “with project” and “without project” were compared by means of PEM using the main indicators of project efficiency—NPV, IRR, PBP, and PI. Substrate blend structure was defined by the direct search method (DSM) to select the probe providing the highest NPV.

Many studies were published about biogas production in various countries. However, only a few works describing the state of the art referring the biogas production in the Russian Federation can be found up to now in the scientific databases [22]. Preliminary results on topics connected with biogas production modeling were published [23–26], as well as biogas potential of agriculture was evaluated for the Tambov region of the Russian Federation [27] by the authors of this study. However, as information about biogas from agricultural feedstock in Russia is still scarce, this paper is to “bridge the gap” by referring biogas production modeling for a typical Russian farm.

The high efficiency (and hence high investment appeal) of biogas technology justified by SM, LPM, WFM, and PEM is suggested to be a strong argument to draw attention to this industry by business and state structures. Therefore, as no works using such a variety of methods and instruments in Russian or in English are presented so far (for any Russian farm), this study is to compensate for this drawback, taking into account Russian peculiarities of farming.

Materials and Methods

Modeling Framework

BGPs normally include fermenters with gasholders, loaders, inclined and submersible mixers, heating units, automation, separator, torch, and gas drier. BGP capacities are based on the capacities of the fermenters. For the application of biogas technology, the number of fermenters and their capacities should be in balance with the capacities of the farm regarding land and substrate production on one hand and the CHPP capacities and electricity demands on the other. In turn, capacities and amounts of CHPPs should be balanced with the farm substrate production capacities, fermenter capacities, and energy demand. Therefore, the optimal CHPP capacities should provide a low loss of processed and sold biogas and low investment costs for the equipment.

Substrate blend inputs and digestate outputs depend on the composition of the substrates and additional ingredients (like water and enzymes) on one hand and the operating parameters of the substrate blend in the fermenter on the other. Thus, the optimal content of the substrate blend should provide both the highest economic effect of the AD process and a trouble-free AD process in the fermenter.

The farm that integrates the AD technology in its production structure should balance the AD equipment set, the production of the substrates, and the regular “usual” production of the farm to achieve the best economic effect.

To achieve these goals, the project efficiency evaluation procedure (EEP) was realized by interlinking the following models and by solving them consistently. The parameters of each substrate and the parameters of the AD process were entered into the simulation model for substrate blend optimization (SBO) to calculate the parameters of the substrate blend and of the digestate fractions. Calculated substrate blend parameters and parameters of digestate fractions were set to the linear model for a fertilizing plan optimization (FPO) together with the crop nutrition parameters, soil parameters, and parameters of fertilizers to calculate the fertilizing plan of the farm. Parameters of the fertilizing plan, prices of resources, and parameters of technological operations were set to the simulation model for the cost plan optimization (CPO) to calculate the cost plan of the farm. The calculated cost plan was set to the linear model for the farm production plan optimization (FPPO) in a situation “without project” with prices of production, production outputs, and parameters of the farm to calculate the farm production plan and cash flows of the farm for the situation “without project”. Calculated cash flows of the farm for the situation “without project” were set to the FPPO in the situation “with project” together

with other data like AD equipment capacities, prices of AD equipment, prices of enzymes, currency exchange rates, and other parameters of the project environment. This operation was conducted to calculate the biogas equipment set, farm production plan cash flows, and the evaluation indicators of the project. The procedure that included linear and simulation models for situations “without project” and “with project” were called the efficiency evaluation procedure (EEP).

For each possible share of substrate (to within 1%), EEP was realized. The substrate blend providing the highest NPV was selected as the most effective one by means of direct-search method (DSM).

Project EEP and data flows in it is schematically presented in Fig. 1. For more details about the mathematical representation, see Supplementary Material.

Despite the fact that the level of efficiency of agricultural production is formed largely by meteorological conditions and the efficiency of planning the structure of acreage and the territorial location of production increases in the case of short-term production planning (for 3 to 5 years) [28], the authors of this study proceed from the fact that equipment lifetime is equal to 20 years. However, it should be kept in mind that the longer the project is the higher the unpredictable economic and political risks are, including currency exchange rate fluctuations, floods, droughts, and others. Moreover, due to unstable Russian economy, Russian farmers prefer to deal with projects with short (medium)-term pay-back periods more. Nevertheless, the authors of this study proceed from the equipment lifetime and the project length is assumed to be estimated at 20 years, although the model allows using much shorter cash flows in general if needed.

Efficiency Evaluation Procedure

Nomenclature

The elements used throughout the simulation model for the biogas project, the notes on efficiency maximization and the subsets of elements are presented in Supplementary Material (Section 1). The meanings of variables and parameters are described separately for each model for the corresponding model in the corresponding section where the model is described.

The Object of Study

The object of study is the farm located in the Sosnovsky municipal district of the Tambov region in the Russian Federation and is a standalone subdivision of LLC “Agro-Vista Tambov” [29]. Having 7500 ha of planting area and 1000 cattle places, the farm keeps 310 milk-producing cows in the

herd. The crop rotation that is used for commodity and feed crop production is presented in Fig. 2.

Simulation Model for Substrate Blend Optimization (SBO)

The simulation model for substrate blend optimization allows calculating optimal inputs and outputs of the biogas plant to meet the requirements referring to the structure of the substrate blend and to find optimal amounts of water and enzymes required for a trouble-free AD process. AD crops, manure, and additional ingredients are combined to provide optimal values of the main operating parameters.

Such parameters of AD products as biogas, CH₄, volume, DM, VS, C:N ratio, N, P₂O₅, and K₂O per t of each substrate (maize green mass, cereal grain, cereal straw, and manure) as well as the content of DM in different fractions of the digestate were taken as input data for SBO to calculate corresponding substrate blend parameters and parameters of different fractions of the digestate. Model output of SBO includes such inputs and outputs of the substrate blend as biogas, CH₄, volume, DM, VS, C:N ratio, N, P₂O₅, and K₂O in corresponding units per t of the substrate blend and contents of N, P₂O₅, and K₂O in kg per t of different fractions of the digestate. For more details, see Supplementary Material (Section 2.1).

Linear Programing for Fertilizing Plan Optimization (FPO)

Within the crop rotation cycle applied on the farm (Fig. 2), a fertilizing plan for each crop was defined. Six combinations of fertilizers are available: mineral fertilizers only, manure with mineral fertilizers, raw digestate with mineral fertilizers, the liquid fraction of the digestate with mineral fertilizers, solid fraction of the digestate with mineral fertilizers, and dried digestate with mineral fertilizers. Each combination of fertilizers corresponds to a separate fertilizing plan.

Considering the nutritional needs of primary crops, soil parameters, parameters for mineral fertilizers, and for manure as a fertilizer, as well as the parameters for different digestate fractions, the LP model for the fertilizing plan was solved to calculate optimal application rates of fertilizers for each field and for each crop on the farm.

For each fertilizing plan including digestates as fertilizers, contents of N, P₂O₅, and K₂O of different fractions of the digestate calculated by SBO were taken as input data for FPO.

The optimal fertilizing plan was found by minimizing fertilizing costs on one hand and by defining the optimal fertilizer application rates on the other. Fertilizing costs in this linear model were taken as an objective function that was minimized by LP to find the optimal fertilizing plan. The optimal fertilizing plan was considering the constraints and conditions associated with the chemical requirements

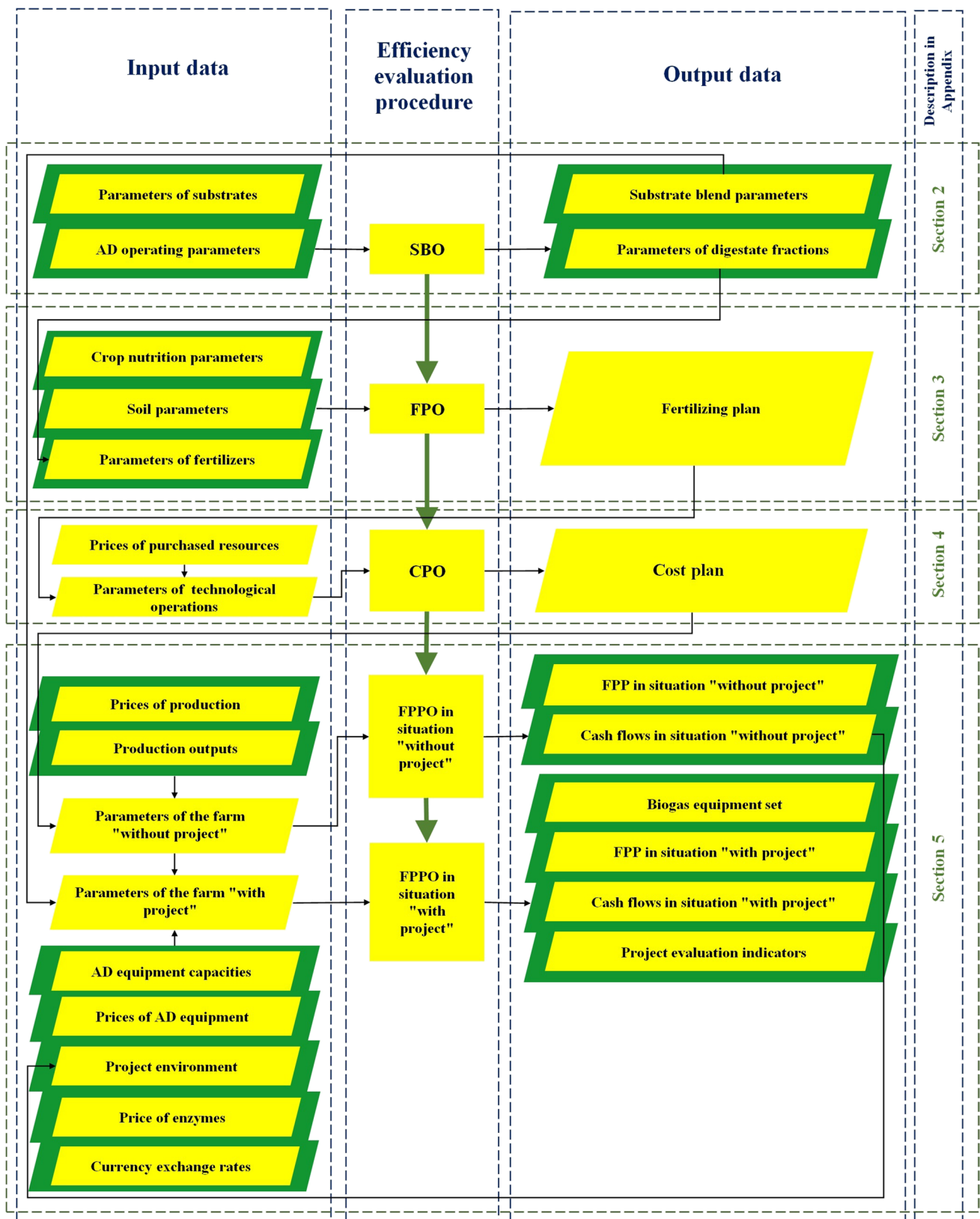
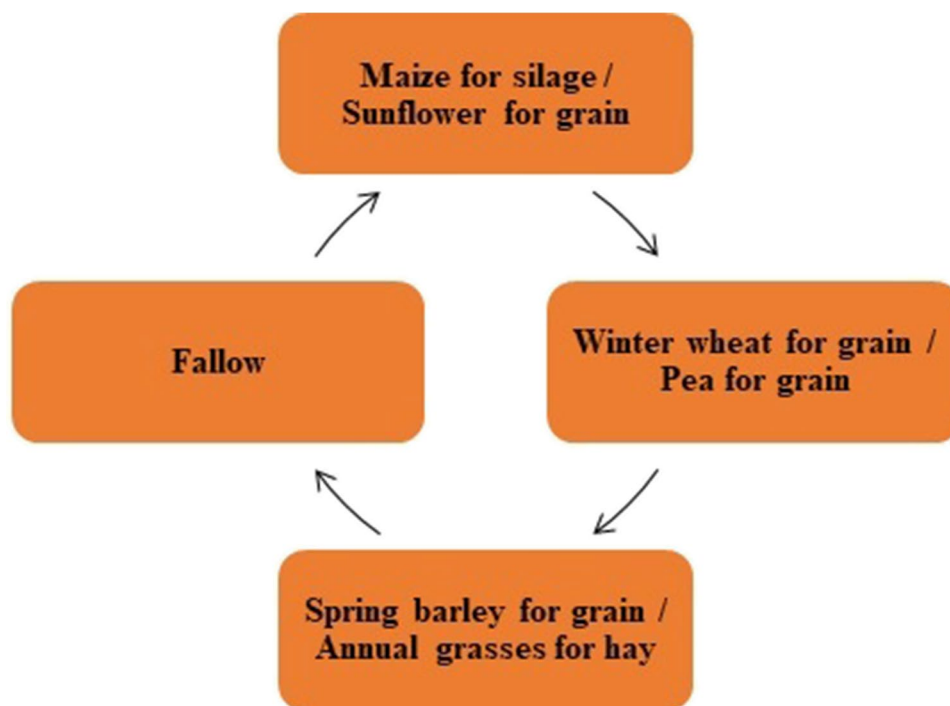


Fig. 1 The scheme and data flows of efficiency evaluation procedure (EEP)

Fig. 2 Crop rotation cycle

of the crops (N, P₂O₅, and K₂O), the chemical content of the fertilizers, the assimilability of chemicals by crops from mineral fertilizers, the assimilability of chemicals by crops from organic fertilizers, the chemical content of the soil, the accessibility of chemicals from the soil, and prices of mineral fertilizers.

Application rates of fertilizers were calculated for each crop and each year of the crop rotation cycle. For more details, see Supplementary Material (Section 3.1).

Simulation Model for Cost Plan Optimization (CPO)

Simulation model for CPO provides an opportunity to define the cost plan of the farm by means of using both the parameters of the technical operations and the fertilizing plan. Fertilizing plan was based on the application rates of fertilizers calculated by FPO for each crop and each year of the crop rotation cycle. CPO was solved to calculate the cost plan for crop production in RUB per ha, animal husbandry in RUB per animal, animal production, and product distribution in RUB per *t*. For more details, see Supplementary Material (Section 4.1).

Linear Programming Model for Farm Production Plan Optimization (FPPO)

Using the parameters of the farm production process taken from the real farm referring to land use, crop production, animal herd structure, animal feeding and bedding, animal production, on one hand, and the cost plan calculated by CPO, substrate blend parameters calculated by SBO and

technical constraints on the AD production, on the other hand, allows to find the optimal farm production plan and to calculate the main farm cash flows.

The linear programming model for FPPO was solved to calculate the optimal farm production plan. The optimal farm production plan was found under the corresponding objective function (i.e., NPV value) maximization by the linear programming method. The optimal farm production plan was found within the constraints and conditions connected with the features of the farm like production potentials, crop rotation cycle, yields of the crops, the productivity of animals, animal herd structure, animals' need for fodders, prices of selling products for situations "without" and "with" project. For more details, see Supplementary Material (Section 5.1).

Scenarios

In scenario A it is assumed that the limit value for electricity production corresponds to the average electricity demand of a farm (885 MWh). In scenario B, it is assumed that all the electricity is sold externally at market price; therefore, electricity production is not limited by demand.

Input Data

The project was evaluated by constant parameters from 2018. Parameters of substrates used as input data in the linear programming model for SB were taken from [30–34] and from the web source of the biogas equipment seller [35]. The values of the parameters describing the technology were

taken from a typical farm in Tambov region, in particular from its technological flow chart. In particular, the input data characterizing the farm (fertilizer requirements of primary crops, parameters of soil and mineral fertilizers, parameters of technological operations, and parameters of the farm production process) originates from a survey of specialists of the farm under research. For this purpose, several study visits to the farm were made for interviews with the director, chief accountant, chief agronomist, chief stock raiser, and other obliged persons of the farm to verify and get complete information for this research. The market prices of purchased resources and commodity products were taken from FSSS sources as an average for the Tambov region or, if not published for the Tambov region, the average for the Central Federal District of the Russian Federation. If data was not collected and published by FSSS for some years due to unknown technical reasons, values of these parameters for 2018 were calculated on the basis of available data by the least-square method (DSM). The parameters of the AD equipment (resources consumption and production capacities of fermenters and CHPPs, prices of the equipment etc.) were taken from the internet for a typical company selling the corresponding equipment. For more details, see Supplementary Material.

Software

The structure of the EEP model matrix includes all the critical parameters of the problem under research. To solve each linear model, the engine COIN-OR CBC (linear solver) of Open Solver for Excel designed by Dr. Andrew Mason and Dr. Iain Dunning was used. More details about the Open Solver for Excel can be found in [36, 37].

Results

Substrate Blend

The substrate blend structure providing the highest NPV within the optimal equipment set as defined by DSM is presented below (see Table 1). A high share of water has to be added to provide optimal DM content in the fermenters.

AD outputs of the substrate blend in scenarios A and B vary considerably. The substrate blend in scenario A is more energy intensive, and, despite the lower output of raw digestate per t of substrate blend, the digestate is richer in fertilizer chemicals (N, P₂O₅, and K₂O). Thus, in scenario A, biogas output exceeds the value of the same parameter in scenario B by 1.10 times. The content of N, P₂O₅, and K₂O of the fertilizer in scenario A is higher than in scenario B. The N content of the fertilizer in scenario A exceeds that of scenario B by 1.25 times. The P₂O₅ content of the fertilizer

Table 1 Substrate blend content in corresponding units per t of substrate blend

Inputs and outputs	Scenario A	Scenario B
Inputs		
Maize green mass in t per t	0.00	0.00
Cereal grain in t per t	0.06	0.05
Cereal straw in t per t	0.00	0.00
Manure in t per t	0.16	0.19
Water in t per t	0.78	0.76
Enzymes in kg per t	7.02	6.77
Outputs		
Volume in m ³ per t	1.26	1.31
DM in t per t	0.09	0.08
VS in t per t	0.07	0.07
Ratio of C and N	14.12	14.44
Biogas in m ³ per t	52.06	47.43
CH ₄ in m ³ per t	30.70	27.65
CO ₂ in m ³ per t	21.36	19.77
Biogas in t per t	0.06	0.06
Raw digestate in t per t	0.16	0.18
N in kg per t	6.31	5.05
P ₂ O ₅ in kg per t	3.88	3.20
K ₂ O in kg per t	4.07	3.73

Table 2 Content of chemicals in different fractions of the digestate in kg per t of digestate

Chemicals	Raw diges- tate	Liquid fraction of digestate	Solid fraction of digestate	Dried digestate
Scenario A				
N	40.42	28.87	144.36	490.81
P ₂ O ₅	24.83	17.74	88.69	301.53
K ₂ O	26.03	18.59	92.97	316.10
Scenario B				
N	28.33	20.24	101.19	344.05
P ₂ O ₅	17.92	12.80	63.99	217.55
K ₂ O	20.94	14.95	74.77	254.23

in scenario A exceeds that of scenario B by 1.21 times. The K₂O content of the fertilizer in scenario A exceeds that of scenario B by 1.09 times (see Table 1).

These differences also caused the variations in chemical concentrations of the fertilizer in different fractions of the digestate. AD outputs of the substrate blend and content of chemicals in different fractions of the digestate in both scenarios are presented in Tables 1 and 2, correspondingly.

Other parameters of the substrate blend are to meet the requirements by providing a trouble-free AD process in the fermenters. For more details, see Supplementary Material (Section 2.2).

Fertilizing Plan

Fertilizing plans do not vary considerably if the scenarios are compared, but the application rates of fertilizers differ significantly in different fertilizing plans within each scenario. The more concentrated the chemicals are in the organic fertilizer (N, P_2O_5 , and K_2O), the lower the application rates of mineral fertilizers. It is also worth mentioning that organic fertilizers make it possible not to apply mineral fertilizers to many crops, as organic fertilizers can considerably cover the plants' need for chemicals (N, P_2O_5 , and K_2O). For more details, see Supplementary Material (Section 3.2).

Costs

Production and post-production costs were calculated in accordance with the technology and application rates of fertilizers for the situation “without project” for both scenarios and for the situation “with project” for scenarios 1 and 2.

In general, the costs per ha do not vary from fertilizing plan to fertilizing plan considerably. However, they differ, and these differences are caused by differences in application rates of fertilizers calculated by FPO. FPO includes a constraint of using no more than 20 t of manure per hectare and no more than 40 kg of N per hectare by the digestates. The solution implies the application of appropriate doses of organic fertilizers to fulfill these constraints for hoed crops. At the same time, solution implies the application of other elements (N, P_2O_5 , and K_2O) with mineral fertilizers to meet the requirements referring to the needs of crops for chemicals, crop assimilability of elements from

the soil, and crop yields. This requirement is met in FPO. The application rates of organic fertilizers were defined at the upper bound: for manure, the application rate is equal to 20 t per ha; and for digestates, the application rate of N is equal to 40 kg per ha. Thus, within each scenario in the fertilizing plans where digestates are applied as fertilizers, application rates of mineral fertilizers do not vary from fertilizing plan to fertilizing plan as well.

The production technology does not vary from fertilizing plan to fertilizing plan considerably—the only fertilizers are different, therefore the total costs per ha do not vary from fertilizing plan to fertilizing plan correspondingly. The costs per ha include costs of fuel, labor of mechanics, labor of drivers, electricity, water, herbicides, fungicides, insecticides, seeds, N, P_2O_5 , and K_2O . The detailed breakdown costs for each kind of resources allocated by fertilizing plans and crops are presented Figs. 3 and 4.

Such parameters as animal husbandry costs in RUB per animal, production costs of animal products in RUB per t and distribution costs in RUB per t are equal in both scenarios as these costs do not depend on the biogas production. For more details, see Supplementary Material (Section 4.2).

However, it should be mentioned that the technology used to model the production process was taken from a typical but certain farm. Thus, a farm owner who wants to model the biogas technology application on his own farm by using the calculation algorithm presented in this study should input features (application rates of fertilizers, fuel expenditures for technological operations, etc.) of his own farm to get the most objective result.

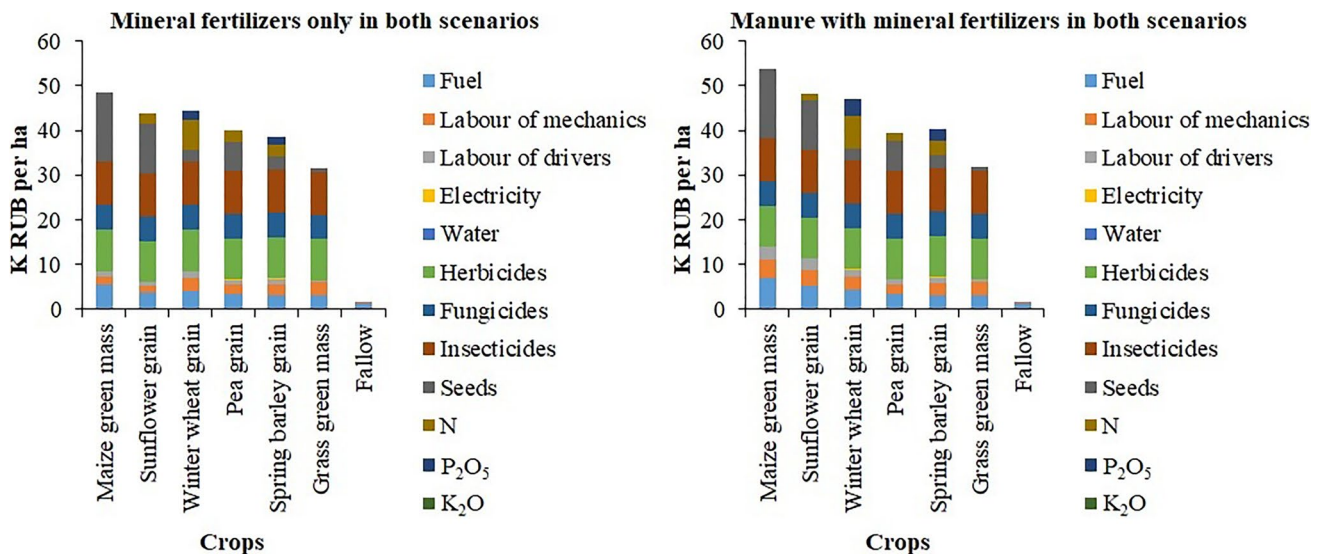


Fig. 3 Production costs of crops in fertilizing plans implying mineral fertilizers only and manure with mineral fertilizers in both scenarios in K RUB per ha

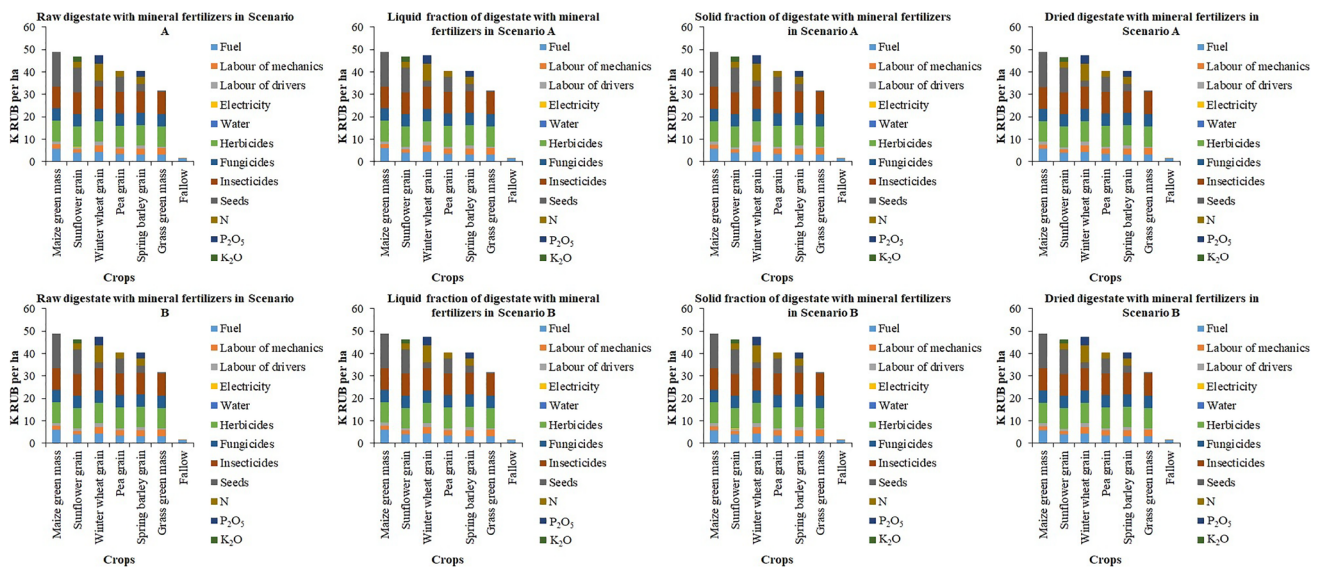


Fig. 4 Production costs of crops in fertilizing plans implying digestates as fertilizers in scenario A and scenario B in K RUB per ha

Farm Production Plan

The main cash flows of the farm were calculated within the main function maximization and the optimization of the farm production plan and presented in the Supplementary Material (Table A42). NPV of the project is estimated at 36.22 M RUB in scenario A and 96.36 M RUB in scenario B. IRR is equal to 35.49% in scenario A and 66.10% in scenario B. PBP is equal to 6 years in scenario A and 3 years in scenario B. PI in scenario A and scenario B are equal to 1.59 and 2.42 correspondingly.

Amount of BGPs, fermenters and CHPPs of 120 kW is the same for both scenarios and is equal to 1 unit of each, and there is 1 additional CHPP of 150 kW in scenario B (see Supplementary Material, Table A47). Therefore, capital costs of the project are estimated at 73.79 M RUB and 81.25 M RUB in scenario A and scenario B, correspondingly. The constant costs of the project (including labor costs, electricity and heat per one BGP) are equal to each other in both scenarios in each year of the project. Other cash flows of the project in each year of the project are presented in Table 3.

The project was evaluated for a period of 20 years with constant parameter values this period. The project changed the structure of the farm production plan in general mainly by “creating” a new revenue from AD products on one hand and by “diversification” of lands by the new kinds of fertilizers on the other.

In the situation “without project” only 78.94% of soils are fertilized solely by mineral fertilizers and 21.06% of lands are fertilized by manure with mineral fertilizers. In the situation “with project” in scenario A, 41.15% of the land is fertilized by the liquid fraction of the digestate with mineral fertilizers and only 39.74% of the land is fertilized by dried digestate with mineral fertilizers. In the situation “with project” in scenario B, 92.77% of lands are fertilized by the liquid fraction of the digestate with mineral fertilizers (see Table 4).

Despite the less energy-intensive substrate blend and despite the less chemical-intensive fractions of the digestate referring to in-fertilizer chemicals, the operating income of the farm in scenario B is considerably higher than in scenario A because of the AD production volumes of the project. The project improved the structure of the farm in scenario B more than

Table 3 Main farm cash flows

Parameter	Situation “without project”	Situation “with project”	
		Scenario A	Scenario B
Constant costs of the project in M RUB		6.72	6.72
Current costs in M RUB	254.12	271.50	272.16
Current revenue in M RUB	275.15	309.71	323.85
Operational income in M RUB	21.03	38.21	51.69
Discount rate in %		19.49	19.49

Table 4 Distribution of lands in ha

Lands in ha	1st field		2nd field		3rd field		4th field
	Maize green mass	Sunflower grain	Winter wheat grain	Pea grain	Spring barley grain	Grass green mass	Fallow
Situation “without project” in both scenarios							
Mineral fertilizers only	256.55	1223.66	1480.20		847.49	632.71	1480.20
Manure with mineral fertilizers		394.80	394.80			394.80	394.80
Situation “with project” in scenario A							
Mineral fertilizers only		25.20	25.20		25.20		25.20
Manure with mineral fertilizers		333.13	333.13		333.13		333.13
Raw digestate with mineral fertilizers							
Liquid fraction of digestate with mineral fertilizers	233.22	538.26	771.49			771.49	771.49
Solid fraction of digestate with mineral fertilizers							
Dried digestate with mineral fertilizers		745.19	745.19		546.68	198.50	745.19
Situation “with project” in scenario B							
Mineral fertilizers only							
Manure with mineral fertilizers		135.50	135.50		135.50		135.50
Raw digestate with mineral fertilizers							
Liquid fraction of digestate with mineral fertilizers	235.60	1503.90	1739.50		769.51	969.99	1739.50
Solid fraction of digestate with mineral fertilizers							
Dried digestate with mineral fertilizers							

the structure of the farm in scenario A—the large scale of the project in scenario B made the project much more profitable.

The farm production plan is presented below (see Table 5). Herd structure is the same in all situations and in both scenarios, so it is not influenced by the project. Herd structure is presented in the Supplementary Material (Table A46).

The daily loaded substrate volume amounts to 10.15 m³ per a day in scenario A and to 32.74 m³ per a day in scenario B. HRT is equal to 236.35 days in scenario A and 73.29 days in scenario B. OLR is equal to 0.62 kg VS m⁻³ day⁻¹ in scenario A and to 1.69 kg VS m⁻³ day⁻¹ in scenario B. Equipment set and capacity utilization of all fermenters are presented in the Supplementary Material (Table A47 and Table A48). For more details referring to the farm production plan, see Supplementary Material (Section 5.2).

Discussion

Along with the approaches presented in [15–21], this study offered a new option of biogas production evaluation on a real farm, taking into account the characteristics of the

specific farm and using SM, LPM, WFM, PEM, and the main indicators of project efficiency: NPV, IRR, PBP, and PI. This article describes the production of biogas within a single farm. The resources for biogas production are taken from the farm; and the produced electricity is used by the farm and sold outside. Digestates are used as fertilizers on the fields of the farm. Thus, biogas production does not depend on any feedstock from the “outside.” Nevertheless, in the case when the biogas technology is widely applied regionwide or countrywide, the biogas production on a farm can be connected with other farms and households by feedstock supplies and energy distribution. The experience of other countries (e.g. Poland [38]) shows that biogas production technology application countrywide can lead not only to benefits like strongly developed agriculture, utilization of animal wastes preventing the emission of methane to the atmosphere, cogeneration as an eco-friendly manner of electricity and heat recovery from waste, but problems on the national level. On the one hand, weak sides of biogas technology like lack of spatial management plans in the local municipalities, high investment costs, high power production costs when compared to other RES, and others should also

Table 5 Farm production plan in corresponding units

Volumes of products and resources	Situation “without project”				Situation “with project”			
	Scenario A		Scenario B		Scenario A		Scenario B	
	Animal feeding/ bedding/ watering	Fertilizing farmer’s own fields	Substrate blending	Selling on a market	Animal feeding/ bedding/ watering	Fertilizing farmer’s own fields	Substrate blending	Selling on a market
Maize silage in kt	4.08				4.08			0.04
Sunflower grain in kt			3.59				3.91	3.91
Winter wheat grain in kt			8.44			0.48	8.60	8.06
Pea grain in kt			2.90				3.40	3.41
Spring barley grain in kt								
Grass hay in kt	0.48				0.48			
Cereal straw in kt	1.03				1.03			0.04
Milk in kt	0.64		1.12		0.64		1.12	1.12
Live weight in kt			0.03				0.13	0.13
Electricity in TJ							3.02	7.56
Heat in TJ		7.90				6.66	3.32	8.32
Manure in kt						1.23		4.07
Raw digestate in kt								
Liquid fraction of digestate in kt						1.07		3.44
Solid fraction of digestate in kt								
Dried digestate in t						60.73		195.35
Water in kt	13.41				13.41			16.71
Enzymes in t							6.06	0.15
Combined fodder in kt	0.48				0.48		0.05	0.48

be taken into account when developing the biogas industry countrywide. On the other hand, threats like the volatility of prices of substrates originating from power-targeted cultivations, and a drop in the prices for utilization of agricultural and food waste must be prevented. In addition, a large number of small biogas plants can create logistical problems connected with the transporting of substrates to many different places and additional financial and environmental costs on a national level [38]. Thus, despite this study analyzing the construction of a biogas plant on a single separate farm, the risks associated with the use of biogas technology on a regional or even national scale should be taken into account.

One of the strong sides of using biogas technology is the production of high-quality organic fertilizers [38]. There is no extensive experience of applying of digestate in Russia, but based on the application rate of N by digestates [31], it can be concluded that the use of digestates is similar to the use of manure, which is common for Russian farms. The experience of other countries (e.g., Brazil [39]) shows that the use of any organic waste for electricity generation can be considered from the point of view of environmental benefits like reducing waste in landfills, increasing economic efficiency and stability of production by saving energy costs, reducing transport fuel volumes and reducing CO₂ emissions [39]. However, the only experience in the future will allow to adapt to the use of new organic fertilizers on Russian farms, taking into account the peculiarities of farming in Russia in different climatic zones and on different soils.

Conclusion

In this study, the efficiency of biogas production on a Russian farm was estimated. The integration of biogas technology into Russian farm production processes is described by the mathematical modeling, taking into account Russian farming peculiarities. The model based on the system of equations and inequalities was solved by means of LP instruments. The economic efficiency of the BGP installation and AD process initiation was estimated with PEM and the main financial sources of the project: NPV, IRR, PBP, and PI. The project was evaluated for a period of 20 years with constant parameter values for this period.

The results show that the project, involving all the parts of the farm, changes farm production structures, taking into account new commodity production as electricity, heat, and digestate. In particular, biogas technology makes animal production more effective as manure has become a more important and valuable intermediate product of the farm, and other products like substrates are used as energy sources.

The model for the biogas project interlinked all parts of the farm, such as lands, crop production, animal

production, AD production, and shows the higher potential effectiveness of such a project on a farm in case when all the produced electricity is sold. The authors believe that this study will awaken the interests of Russian farmers and politicians, potential investors, and biogas equipment producers to produce biogas in Russia and other countries.

However, at the same time, biogas is a relatively new scientific field, energy sub-industry, and market sector for Russia. Lack of experience in the use of biogas technology, political barriers, and market monopolies in the Russian energy market cause uncertainties regarding the economic efficiency of biogas technology. Biogas technology can be very profitable for farms and extremely useful for sustainable rural development in the Russian Federation. However, it is also highly influenced by market variability and still not supported by the government.

Such unstable market and production factors like crop yields, animal productivity, costs and prices of resources, and commodity production have a high impact on biogas projects. Therefore, the uncertainty caused by the production, market variability, and policy barriers is the objective for the project evaluation with methods of risk analysis in a subsequent study.

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Declarations

Ethics Approval No experiments with humans or animals were performed in the study. Ethical clearance was not required.

Consent to Participate All authors contributed to the manuscript.

Consent for Publication All authors agreed to publication.

Competing Interests The authors declare no competing interests.

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