Solving the problem of logistics planning in the application of biotechnology in the energy sector of the region

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Abstract. The article provides a solution to the problem of logistics planning to implement the possibility of using biotechnology in the energy sector. The technology used is the production of biogas from animal wastes. Objects participating in the biogas production process are animal husbandry enterprises that are a source of raw materials, biogas complexes that produce biogas, as well as heat sources where biogas is converted into heat energy. The structure of the optimal location of objects participating in the biogas production process on the territory is built on the example of the Udmurt Republic. An economic criterion for minimizing the cost of biogas production and its delivery to consumers was chosen as an optimization criterion. For the numerical solution of the optimization problem, a genetic algorithm with real coding was implemented, and parallel computations were carried out. The maximum volume of biogas production has been calculated, at which it is economically feasible to replace natural gas with biogas for a given territory. For this volume, the optimal number was determined and the optimal territorial distribution of biogas complexes was constructed, which supply heat sources with fuel, the number of which was also found as a result of solving the optimization problem.

1. Introduction
The possibilities of using living organisms and products of their vital activity are used to solve technological problems [1-3]. Such problems arise naturally in many industries and agriculture. The branch of human activity where biotechnology can be used includes the production of biogas from animal wastes [4-6].

The use of biotechnology for biogas production allows obtaining a number of useful practical effects. First, it reduces the negative impact that human activities have on the ecological system [7]. Secondly, the proposed approach to gasification obviously makes it possible to ensure energy security. The use of waste products of living organisms for biogas production contributes to the emergence of new types of production [8,9]. Also, rational use and logistic planning of the location of biogas production facilities gives a positive economic effect [10].

The heat supply system of the region has a distributed structure. To provide this system with biogas, the issues of organizing its production from animal wastes were considered in conjunction with accompanying measures. In particular, logistics planning for the location of biogas production facilities is carried out taking into account the costs of re-equipment of heat sources.

Logistic planning involves the mathematical calculation and implementation of the optimal structure of production and placement of enterprises for the processing of raw materials (animal wastes) into
intermediate products (biogas) and into final products (heat energy). The construction of mathematical models and logistic planning tools makes it possible to rationally use the available resource opportunities and, accordingly, to achieve the best values of the placement efficiency indicator, which consists in minimizing costs or maximizing profits [11,12].

2. Materials and research methods
2.1. Features of biotechnology for the production of biogas from animal wastes
Biogas is produced by anaerobic methane digestion of organic raw materials. Biogas composition: 55-75% methane, 25-45% carbon dioxide. After cleaning biogas from carbon dioxide, biomethane is obtained, which is a complete analogue of natural gas and differs from it only in origin.

The technological scheme for the biogas production is as follows [13]. Liquid biowastes are pumped into the tank for collection and homogenization of raw materials. Conveyor belt, trucks or other means to a special auger loader deliver solid wastes. From the homogenization tank and the solid waste loader, the biomass enters the reactor (fermenter). A fixed temperature for microorganisms is maintained inside the reactor. Methane-forming bacteria in anoxic conditions can release gas in the temperature range from 0°C to 70°C. Inside the reactor, the biomass is constantly mixed mechanically or hydraulically. The average fermentation time inside the reactor (depending on the substrates) is 20-40 days. During this time, organic matter inside the biomass is metabolized (transformed) by microorganisms. The output is 2 products: biogas and biofertilizers (composted and liquid substrate).

It is most efficient to organize the biogas production from wet and liquid biomass, large volumes of which are generated at animal husbandry enterprises. These include, in particular, poultry farms, pig farms, cattle farms. It is most rational to locate biogas complexes near animal husbandry enterprises and supply heat sources located in the vicinity with the help of a gas pipeline network.

2.2. Mathematical model of logistics planning for solving the problem of applying biotechnology in the region
There are three basic elements in the problem statement (figure 1):
- animal husbandry enterprises, which are a source of raw materials for biogas production, the total number of livestock enterprises is $I$, the index $i$ reflects the number of the enterprise ($i = 1, I$);
- biogas complexes, which produce biogas, the total number of complexes is $J$, the index $j$ reflects the number of the biogas complex ($j = 1, J$);
- heat sources where biogas is converted into heat energy, the total number of heat sources is $K$, the index $k$ reflects the number of the heat source ($k = 1, K$).

![Diagram](https://via.placeholder.com/150)

**Figure 1.** Scheme of the relationship of animal husbandry enterprises, biogas complexes and heat sources.
There are a number of $K$ heat sources. For the production of heat energy, animal wastes are used, that are accumulated at livestock enterprises, the total number of enterprises is equal to $I$. It is required to find the volumes of biogas production in each of the $J$ potential points of its production – biogas complexes. Heat production points are heat sources. The possible territorial location of biogas complexes is determined in advance, while it may or may not coincide with the provisions of livestock enterprises and heat sources.

The target functional is the criterion for minimizing the total costs of heat production, taking into account the costs of producing and supplying biogas:

$$Z = \tilde{Z} + \hat{Z} \rightarrow \min.$$  

where $Z$ – total costs for the production of biogas and heat energy, rubles/year; $\tilde{Z}$ – costs of transporting animal waste, biogas production and delivery to heat sources, rubles/year; $\hat{Z}$ – costs of processing biogas into heat energy at heat sources, rubles/year; $v_j$ – volume of biogas production at the $j$th point of its production, m³/year; $D_k$ – the volume of heat energy output at the $k$th heat source, Gcal/year; $F_j(V_j)$ – costs of processing animal waste into biogas at the $j$th biogas complex, rubles/year; $E_k(D_k)$ – costs of processing biogas into heat energy at the $k$th heat source, rubles/year; $g_{il}$ – unit costs for the transportation of raw materials used for biogas production between the $i$th livestock enterprise and the $j$th biogas complex, rubles/m³; $g_{jk}$ – unit costs for transportation of one unit of biogas volume between the $j$th biogas complex and the $k$th heat source, rubles/m³; $x_{ijk}$ – the share of heat energy that is produced at the $k$th heat source, obtained from the raw materials of the $j$th biogas complex when consuming the raw materials of the $i$th livestock enterprise; $\gamma$ – consumption coefficient of 1 m³ of biogas for the production of 1 Gcal of heat energy; $\alpha$ – consumption coefficient of 1 m³ of animal wastes for the production of 1 m³ biogas.

Controllable variables are variables $x_{ijk}$, that determine the share of participation of the $j$th biogas complex in meeting the demand of the $k$th heat source.

The costs of processing animal waste into biogas $F_j(V_j)$ are determined on the basis of technical and economic calculations:

$$F_j(V_j) = a_j V_j + A_j \Theta(V_j), \quad j = \overline{1, J},$$

where $a_j$ – specific conditionally fixed costs for the production of a unit of biogas volume at the $j$th biogas complex, rubles/m³; $A_j$ – conditionally fixed costs for the entire production of biogas at the $j$th biogas complex, rubles/year; $\Theta(V_j)$ – Heaviside function: $\Theta(V_j) = \begin{cases} 0, & V_j < 0; \\ 1, & V_j \geq 0. \end{cases}$

The cost of converting biogas into heat energy:

$$E_k(D_k) = b_k D_k + B_k \Theta(D_k), \quad k = \overline{1, K},$$

where $b_k$ – conditionally fixed costs for the production of a unit of heat energy at the $k$th heat source, rubles/Gcal; $B_k$ – conditionally fixed costs for the entire production of heat energy at the $k$th heat source, rubles/year.

The following ratios are accepted as constraints:
\[ V_j = \tau \sum_{i=1}^{J} \sum_{k=1}^{K} x_{ijk} D_k, \quad j = 1, J; \quad D_k = D_k \sum_{i=1}^{I} \sum_{j=1}^{J} x_{ijk}, \quad k = 1, K; \]  \tag{4}

\[ \alpha \tau \sum_{j=1}^{J} x_{ijk} D_k \leq W_i; \quad \sum_{i=1}^{I} \sum_{j=1}^{J} x_{ijk} = 1; \quad x_{ijk} \in [0, 1], \quad i = 1, I, \quad j = 1, J, \quad k = 1, K. \]  \tag{5}

where \( W_i \) – the volume of raw materials at the \( i \) th livestock enterprise used for biogas production, m\(^3\)/year.

Relationships (4) establish a balance between the volume of biogas production at biogas complexes and the demand for it at heat sources. The first inequality (5) determines the balance between the required volume of biogas and the potential of the raw material base of livestock enterprises. The second expression (5) reflects the condition for biogas to satisfy all considered heat sources.

2.3. Algorithm for the numerical solution of the logistic planning problem

The mathematical model (1)-(5) belongs to the class of nonlinear optimization problems [14]. The search for the optimal solution in this case is complicated by the large dimension of the vector of the sought solutions, as well as by the specifics of the problem, which is the impossibility of differentiating the objective function [15]. In this regard, the main problem is the choice of a method for the numerical solution of the optimization problem (1)-(5). The solution method is based on a genetic algorithm with real coding. A block diagram of this algorithm using parallel computing is shown in figure 2.

![Block diagram of a genetic algorithm using parallel computing.](image)

The search for a solution to the problem includes 5 stages. 1) Formation of the initial population of individuals. 2) Assessment of the fitness of individuals. 3) Application of genetic operators within each thread: selection, crossing and mutation. 4) Migration of individuals – movement of individuals from one thread to another. 5) The choice of the optimal solution to the problem - the best individual of each thread is compared with the best individuals of other threads, thereby determining the solution.
The overall speed of finding the optimal solution was increased by dividing the population into several threads. Intra-thread operations were performed by separate processors of the computing device.

3. Research results

In accordance with the model (1)-(5) and using the algorithm for the numerical solution of the problem on the example of the Udmurt Republic, an optimal plan for the location of biogas complexes in the region was obtained (figure 3).

The organization of biogas complexes requires large financial investments. Reducing the cost of producing biogas and heat energy based on it is achieved due to large production volumes that can be achieved using raw materials from large livestock enterprises. Further increase in production volumes is achieved through smaller enterprises. In this regard, a parametric problem arises of determining the largest economically viable volume of biogas production, at which the total cost of heat energy from biogas, including the cost of its production, does not exceed the cost of heat energy from natural gas, including the cost of purchasing it.

![Figure 3. Optimal layout of biogas complexes.](image-url)

To solve the problem, a mathematical model (1)-(5) is used, in which the optimization criterion is to minimize the cost of heat energy obtained from biogas, if a given volume of its production is ensured. Figure 4 shows the obtained optimal values of the objective function \( Z \) – the cost of heat energy – for each of the given volumes of biogas production \( V \). Figure 4 also shows the dependence of the cost of heat energy obtained from natural gas on its volume produced. The increase in the volume of...
biogas production due to smaller livestock enterprises leads to a faster growth in the cost of biogas compared to the fixed cost of natural gas, which also affects the cost of heat energy.

Calculations have shown that at $V > 70$ million m$^3$/year the use of biogas to replace natural gas in the conditions of the Udmurt Republic is economically unprofitable. The optimal layout of production, which provides the volume of 70 million m$^3$ of biogas per year, includes 16 biogas complexes located near the largest livestock enterprises, supplying fuel to 62 heat sources (figure 3).

Calculations have shown that in this case the total costs of heat production, including fuel costs, will amount to 215 million rubles/year. The average cost of producing heat energy obtained from biogas for the selected heat sources will be equal to 701 rubles/Gcal.

Figure 5 shows the dependences of the annual economic effect $E$ obtained from replacing the use of natural gas with biogas at heat sources, depending on the volume of its production. This value is determined by the difference between the total cost of heat production using natural gas and biogas.

In the process of biogas production, environmentally friendly organic fertilizers are formed. In addition, wastes from animal husbandry enterprises are environmentally hazardous substances, their utilization in the biogas production eliminates environmental fines. Taking into account the income from the sale of solid biofertilizers, the economically profitable volume of biogas production in the Udmurt Republic increases from 70 to 100 million m$^3$/year, and the maximum economic effect – from 20 to 55 million rubles/year.

4. Conclusion
The problem of logistics planning has been solved to implement the possibility of using biotechnology in the energy sector on the example of the Udmurt Republic. The technology used is the production of biogas from animal wastes. Objects participating in the biogas production process are animal husbandry enterprises that are a source of raw materials, biogas complexes that produce biogas, as well as heat sources where biogas is converted into heat energy. The structure of the optimal location of objects participating in the biogas production process on the territory of the Udmurt Republic has been built from the point of view of the criterion for minimizing the cost of its production and delivery to the consumer. It was found that the maximum volume of biogas production, at which it is economically feasible to replace natural gas with it, is 70 million m$^3$ per year. For this volume, the optimal number has been determined and the optimal territorial distribution of biogas complexes has been built, supplying 62 heat sources with fuel. Taking into account the income from the sale of biofertilizers and the exclusion of environmental penalties, the economically profitable volume of biogas production increases to 100 million m$^3$ per year.
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