Engineering of renewable fuels in the energy complex of the region

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Abstract. The article discusses the solution to the problem of the integrated use of renewable fuels in order to minimize ecological damage to the environment. A mathematical model has been developed that operates with averaged values of stocks of raw materials and fuel requirements. It allows you to determine the optimal number of enterprises for the production of each type of fuel, while obtaining the final formulas characterizing the schemes for the optimal location of production, as well as the relationship between these indicators. Applied calculations were carried out on the example of the Udmurt Republic.

1. Introduction
Environmental engineering in the modern world is of great practical importance. It is implemented as a set of solutions to minimize environmental damage. When solving practical issues of energy supply to regional socio-economic systems, the use of methods and techniques of environmental engineering allows you to avoid negative impact on ecosystems. One of the solutions proposed in the framework of environmental engineering is the use of renewable fuels, the choice of which type is determined based on the capabilities and characteristics of a particular region. The advantages of renewable fuels in terms of maintaining a balance in ecosystems are discussed in detail in [1-3].

This paper considers the issues of engineering of renewable fuels on the example of the energy complex of one of the Russian regions – the Udmurt Republic. We consider the waste generated from the tree treatment and processing as a fuel that can be renewed [4, 5]. To realize the possibility of practical use of environmentally friendly renewable fuels at the regional level, Concepts for the provision of renewable fuel to local heat supply systems are being developed in many regions of the Russian Federation (see, for example, [6-8]).

This article provides a calculation of the optimal parameters for the location of enterprises for the production of wood fuels to supply a distributed heat supply system in the region. Numerical calculations are given for the example of the Udmurt Republic.

When organizing production on a certain territory, important parameters are the volume of products produced at each enterprise and their quantity, the distance of transportation of raw materials to enterprises and products to consumers. It is also often necessary to make a choice of production of products among several interchangeable types. The construction of mathematical models for the optimal location of production allows you to determine the parameters, at which the minimum cost of production is ensured or the total profit is maximized [9-11].
2. Materials and research method

Engineering calculations for the use of renewable fuels in the region’s energy system are carried out on the basis of analytical transformations and calculations. An analytical approach to the study of facility location parameters becomes possible under the assumption of a uniform distribution of raw materials stocks and demand for fuel over the territory. This assumption is not purely author's; the use of such simplifications can be found in the literature, in particular, the work [11] solves the problem of finding the optimal number of enterprises producing a certain product, the demand for which is uniform in the territory under consideration. A numerical solution to the problem of optimal placement of wood fuel production points for a given and discrete location of raw material suppliers and product consumers was obtained in [6]. The result presented below, on the one hand, allows us to construct an estimate of the solution to the optimization problem for the placement of objects on the territory with a sufficiently high accuracy, on the other hand, it allows testing numerical algorithms for a more general optimization problem, for example, considered in [6]. The paper defines new relationships between the parameters of the optimal facility location and this is a contribution to the development of analytical methods for solving the location problem used in [11].

The formula for calculating the cost of heat energy using wood fuel has the form [12]

\[ C = \tau \sum_{i=1}^{M} \left( a_i + \frac{b_i}{v_i} + g_i' L_i' + g_i'' L_i'' \right) \eta_i D_i + \sum_{i=1}^{M} \left( \tilde{a}_i + \tilde{b}_i \right) D_i \text{ rubles/year} \]  

(1)

where \( \tau \) is the caloric equivalent, t.f.e./Gcal; \( M \) is the number of wood fuels; \( a_i \) are conditionally fixed costs per unit of production of the \( i \) th fuel type \((i = 1, M)\), rubles/t.f.e. (t.f.e. is ton of fuel equivalent); \( b_i \) are conditionally fixed costs for the entire volume of production of the \( i \) th fuel type, rubles/year; \( v_i \) is the volume of production of the \( i \) th fuel type at the enterprise, t.f.e./year; \( g_i' \) are costs for the transportation of raw materials for the production of the \( i \) th fuel type, rubles/t.f.e./km; \( L_i' \) is the distance of transportation of raw materials to the enterprise for the production of the \( i \) th fuel type, km; \( g_i'' \) are costs for transportation of the \( i \) th fuel type, rubles/t.f.e./km; \( L_i'' \) is the distance of transportation of the \( i \) th fuel type to the heat source, km; \( \eta_i \) is the ratio of the volume of generated heat energy on the \( i \) th fuel type to its useful output (also takes into account the associated costs of the heat source); \( D_i \) is the volume of heat production from heat sources using the \( i \) th fuel type, Gcal/year; \( \tilde{a}_i \) are unit conditionally fixed costs for the production of heat energy on the \( i \) th fuel type, rubles/Gcal; \( \tilde{b}_i \) are general conditionally fixed costs for the production of heat energy using the \( i \) th fuel type, rubles/year; \( u \) is the volume of heat production at the heat source, Gcal/year.

Let us define the minimization of the cost of heat production (1) as a criterion for optimizing the location of wood fuel production. The limitation on the volume of heat production using various types of fuel is determined by the sum

\[ \sum_{i=1}^{M} D_i = D \]  

(2)

where \( D \) is the total volume of heat energy production, Gcal/year.

In [6], a methodology is given that determines the cost of fuel production. This technique is abstracted from the specific location of raw materials sources and fuel consumers, using only their total characteristics, given per unit area of the considered territory.

\[ D = \sum_{i=1}^{M} D_i \]
where \( \rho_i^f \) are stocks of raw materials required for the production of the \( i \) th fuel type, units/year/km\(^2\) (units = \{t, m\(^3\}\}); \( \rho^f \) is the volume of heat energy production at heat sources, Gcal/year/m\(^2\); \( R_i \) are stocks of raw materials for the production of the \( i \)th fuel type in the territory \( S_i^f \), units/year; \( S_i^f \) is the area of the territory of supplied heat sources, km\(^2\).

Thus, the calculations will be carried out on the assumption of an even distribution of raw materials reserves and the need for fuel, which, in particular, implies the equality of the unit volumes of heat energy production using various fuel types

\[
\rho_i^f = \frac{D_i}{S_i^f}, \quad i = 1, M
\]  

(5)

where \( \rho_i^f \) is the volume of heat energy production using the \( i \)th fuel type, Gcal/year/km\(^2\); \( S_i^f \) is the territory where heat sources work using the \( i \)th fuel type, km\(^2\).

The volume of fuel production at the enterprise \( v_i \) is calculated according to the formula

\[
v_i = \frac{\tau \eta_i D_i}{N_i}, \quad i = 1, M
\]  

(6)

For the production of the \( i \)th fuel type, the number of enterprises \( N_i \) is used, which can be calculated by the formula

\[
N_i = \frac{S_i^f}{\sigma_i^f}, \quad i = 1, M
\]  

(7)

In formula (7), \( \sigma_i^f \) is the area of the territory of fuel supply by one enterprise for the production of the \( i \)th fuel type, km\(^2\). This parameter is related to the distance of fuel transportation by the ratio [6]

\[
\sigma_i^f = \left( \frac{1}{\gamma \beta} L_i^2 \right)^{\frac{1}{2}}, \quad i = 1, M
\]  

(8)

where \( \gamma \) is the coefficient of roads curvature (\( \gamma \geq 1 \)); \( \beta \) is the coefficient of the ratio between the weighted average distance along a straight line of each point of the area from the center and the area of this territory.

The road curvature coefficient \( \gamma \) shows how many times the products transportation distance along the roads between the points of raw material preparation, fuel production and heat sources exceeds the distance of objects from each other in a straight line. This indicator is calculated based on information on the location and characteristics of roads in the area under consideration. The coefficient \( \beta \) depends on the form of coverage of the territory of product supply by one enterprise. In particular, with a circular shape of the supply area, the value of the indicator is 0.376, for a square area – 0.383.

Formulas (5) – (8) imply the following relationship between the volume of production of the \( i \)th fuel type at the enterprise and the distance of fuel transportation to the heat source:
\[ v_i = \tau \eta_i \rho_i \left( \frac{1}{\gamma \beta} L_i^f \right)^2, \quad i = 1, M \]  

(9)

If we denote \( \alpha_i \) is the consumption coefficient of the number of raw materials units for the production of a unit of the \( i \) th fuel type, units/t f.e., then the area of the territory for harvesting of raw materials for the production of the \( i \) th fuel type \( S_i' \) \( (S_i' \leq S_i') \) will be determined by the formula

\[ S_i' = \alpha_i \frac{S_i'}{R_i} \tau \eta_i D_i, \quad i = 1, M, \text{ km}^2 \]  

(10)

Assuming \( S_i' = N_i \sigma_i', S_i' = N_i \sigma_i' \), where \( \sigma_i' = \left( \frac{1}{\gamma \beta} L_i' \right)^2 \) is the raw material harvesting area for one enterprise, expression (10) is reduced to the relationship between the distance of transportation of raw materials and fuel

\[ L_i' = L_i' \sqrt{\frac{\tau \eta_i D_i}{R_i}} = L_i' \sqrt{\tau \alpha_i \eta_i \frac{\rho_i}{\rho_i'}, \quad i = 1, M} \]  

(11)

Substituting instead of the values \( v_i \) and \( L_i' \) the right-hand sides of equalities (9), (11) into expression (1), we obtain the following form of the formula for calculating the cost of heat production:

\[ C = \tau \sum_{i=1}^{M} \left( a_i + \frac{b_i}{\tau \eta_i \rho_i'} \left( \frac{1}{\gamma \beta} L_i' \right)^2 \right) \left( g_i' \sqrt{\tau \alpha_i \eta_i \frac{\rho_i'}{\rho_i'}} + g_i' \right) \eta_i D_i + \sum_{i=1}^{M} \left( \tilde{a}_i + \frac{\tilde{b}_i}{u} \right) D_i \]  

(12)

Thus, the target cost function is reduced to the dependence on the distance of fuel transportation and the volume of heat production for each type of fuel:

\[ C = F(L_1', ..., L_M'; D_1, ..., D_M) \]  

(13)

Unknown \( L_i' \) are determined from the condition

\[ \frac{\partial C}{\partial L_i'} = \tau - \frac{2b_i}{\tau \eta_i \rho_i'} \left( \frac{1}{\gamma \beta} L_i' \right)^2 + \left( g_i' \sqrt{\tau \alpha_i \eta_i \frac{\rho_i'}{\rho_i'}} + g_i' \right) \eta_i D_i = 0, \quad i = 1, M \]  

(14)

Whence we get the optimal transportation distance for each type of fuel, independent of \( D_i \):

\[ (L_i')_{\text{opt}} = \sqrt{\frac{2b_i}{\tau \eta_i \rho_i'} \left( \frac{1}{\gamma \beta} L_i' \right)^2 \left( g_i' \sqrt{\tau \alpha_i \eta_i \frac{\rho_i'}{\rho_i'}} + g_i' \right)}, \quad i = 1, M \]  

(15)

Since the Hesse matrix
\[ H(C) = \left[ \frac{\partial^2 C}{\partial L_j^f \partial L_k^f} \right]_{j,k=1}^M \]

is positive-definite for any fixed \( D_i \), then the distances \( (L_j^f)_{\text{opt}} \) calculated by formula (15) provide a minimum of function (12).

The optimal volumes of heat production using various types of fuel \( (D_i) \) are determined from the solution of the problem formulated above with a linear (see formula (12)) objective function in terms of parameters \( D_i, i = 1, M \):

\[
C = F((L_j^f)_{\text{opt}}, ..., (L_M^f)_{\text{opt}}; D_1, ..., D_M) \rightarrow \min
\]

subject to the constraint (2).

3. Research results

To calculate the optimal parameters for the location of wood fuel production on the territory of the Udmurt Republic, we will use the data given in [4]. The calculation is carried out for two types of wood fuel: chips and pellets. Wood chips are obtained by crushing and naturally drying wood pulp. We suppose that pellets are produced near wood processing enterprises, therefore, we will neglect the transport costs for the supply of raw materials for them. Since the production of pellets involves the use of additional operations of crushing, pressing and drying of wood raw materials, this leads to an increase in the cost of their production in comparison with wood chips. Based on technical and economic calculations, the dependences of the cost of chips and pellets on transportation costs and production volume were determined

\[
c_{ch} = a_{ch} + \frac{b_{ch}}{v_{ch}} + g_{ch}^f L_{ch}^f + g_{ch}^r L_{ch}^r = 154.1 + \frac{361,941.1}{v_{ch}} + 5.1 L_{ch}^f + 3.1 L_{ch}^r \text{ rubles/m}^3
\]

\[
c_{pl} = a_{pl} + \frac{b_{pl}}{v_{pl}} + g_{pl}^f L_{pl}^f + g_{pl}^r L_{pl}^r = 1,447.9 + \frac{764,087.7}{v_{u}} + 2.1 L_{pl}^f \text{ rubles/t}
\]

Here, the variables with the index ‘ch’ refer to wood chips, those with the index ‘pl’ to pellets. Taking into account that the calorific value is 0.266 t f.e./m³ for chips, and 0.600 t f.e./t for pellets, we get \( a_{ch} = 579.3 \text{ rubles/t f.e.}, b_{ch} = 361,941.1 \text{ rubles/year}, g_{ch}^f = 19.1 \text{ rubles/t f.e./km}, g_{ch}^r = 11.7 \text{ rubles/t f.e./km} \) for chips; \( a_{pl} = 2,413.2 \text{ rubles/t f.e.}, b_{pl} = 764,087.7 \text{ rubles/year}, g_{pl}^f = 3.5 \text{ rubles/t f.e./km} \) for pellets.

The considered region has a total annual supply of heat energy from heat sources equal to \( D = 56,277 \text{ Gcal/year}. \) It is located on an area \( S^f = 9,460 \text{ km}^2. \) In the region, raw materials stocks for the wood chips production are \( R_{ch} = 55,960 \text{ m}^3/\text{year}, \) raw materials stocks for pellets \( R_{pl} = 22,480 \text{ km}^3/\text{year}. \) The unit volume of heat energy production is \( \rho^F = 5.949 \text{ Gcal/year/km}^3, \) the unit stocks of raw materials for wood chips are equal to \( \rho_{ch}^F = 5.915 \text{ m}^3/\text{year/km}^2. \) The coefficients of the generated heat energy to its useful supply are \( \eta_{pl} = 1.169 \) and \( \eta_{ch} = 1.232 \) for pellets and chips, respectively. Cost coefficients for the conversion of fuel into heat energy are \( \bar{a}_{pl} = 289.4 \text{ rubles/Gcal}, \bar{b}_{pl} = 299,582.8 \)
rubles/year for pellets. For wood chips, these ratios are $a_{ch} = 294.3$ rubles/Gcal, $b_{ch} = 286,775.4$ rubles/year.

Heat release at the heat source is equal to $\mu = 938$ Gcal/year. For further calculations, we also take $\gamma = 1.43$, $\beta = 0.383$ [4].

Next, we substitute the numerical values for our problem into formula (12) and obtain the final form of the objective function.

If calculations are made for cases where the total volume of heat energy is produced only on chips or on pellets, then the graphs of the dependence of the heat energy cost on the transport distance for the corresponding type of fuel are shown in figure 1.

Using formula (15), we can calculate the optimal transport distance for the type of fuel of interest to the researcher. So, for wood chips, this value is $(L_{ch})^{opt} = 19.7$ km, the cost of heat energy production is $C = 47.5$ million rubles/year, the required number of enterprises is $N_{ch} = 7.34$, the volume of fuel production at the enterprise is $v_{ch} = 1,351$ t.f.e./year.

In the case of using only pellets as fuel, the optimal distance of their transportation will be $(L_{pl})^{opt} = 50.5$ km, the cost of heat production $C = 59.5$ million rubles/year, the required number of enterprises $N_{pl} = 1.11$, the volume of fuel production at the enterprise $v_{pl} = 8,475$ t.f.e./year. Having rounded up the number of enterprises for the preparation of chips and pellets to whole values, we obtain the following adjusted characteristics: for chips – $N_{ch} = 7$, $(L_{ch})^{opt} = 20.1$ km, $v_{ch} = 1,416$ t.f.e./year and the cost of heat production $C = 47.5$ million rubles/year; for pellets – $N_{pl} = 1$, $(L_{pl})^{opt} = 53.3$ km, $v_{pl} = 9,408$ t.f.e./year and $C = 59.5$ million rubles/year.

Substituting the found distances $(L_{ch})^{opt}$ and $(L_{pl})^{opt}$ into the objective functional (12) with the numerical values of the coefficients, we obtain

$$C = 843.7D_{ch} + 1,057.6D_{pl} \text{ rubles/year}$$

The total volume limitation of heat energy production is...
\[ D_{ch} + D_{pl} = 56,277 \text{ Gcal/year} \]

Let us introduce the following characteristic, which determines the ratio of the volume of heat energy production on pellets to its total volume on all types of fuel:

\[ \omega_{pl} = \frac{D_{pl}}{D_{ch} + D_{pl}} \]

The stocks of raw materials for the production of wood chips are sufficient for the production of heat energy in the amount of 104,105 Gcal/year. Stocks of raw materials for pellets can provide heat production in the amount of 43,140 Gcal/year. Obviously, it is necessary that the stocks of raw materials are not less than the requirements for fuel for the region under consideration. Thus, the maximum value of the ratio of the volume of heat energy production on pellets to its total volume is limited by the value \( \omega_{pl}^{\text{max}} = 0.77 \). The table 1 shows the nominal and adjusted (for integer values of the number of enterprises) optimal parameters for the location of wood fuel production at different \( \omega_{pl} \). Figure 2 shows the optimal layout for the production of fuel from wood waste.

| Parameter \( \omega_{pl} \) | Type of fuel | \( (L_i')^\text{pt} \) km | \( N_i \) | \( v_i \) t f.e./year | \( c \) million rubles/year | \( (L_i')^\text{pt} \) km | \( N_i \) | \( v_i \) t f.e./year | \( C \) million rubles/year |
|---------------------------|-------------|---------------------|-------|---------------------|---------------------------|---------------------|-------|---------------------|---------------------------|
| 0                         | Chip        | 19.7 7.34 1.351     |       | 47.5                | 20.1                      | 7                  | 1.416 | 47.5                |
|                           | Pellets     | – – –               |       | – – –               | – – –                     | – – –               | – – – | – – –               |
| 1/2                       | Chip        | 19.7 3.67 1.351     |       | 53.5                | 18.8                      | 4                  | 1.239 | 53.6                |
|                           | Pellets     | 50.5 0.56 8.475     |       | 37.7                | 1                        | 4.704              |       |                     |
| \( \omega_{pl}^{\text{max}} \) | Chip        | 19.7 1.71 1.351     |       | 56.7                | 18.2                      | 2                  | 1.157 | 56.7                |
|                           | Pellets     | 50.5 0.85 8.475     |       | 46.6                | 1                        | 7.212              |       |                     |

Thus, the developed mathematical model, operating with the averaged values of stocks of raw materials and fuel requirements, makes it possible to determine the optimal number of enterprises for the production of each type of fuel, while obtaining the final formulas for determining the interrelationships of the parameters of the optimal facility location.

The total production of wood chips amounted to 9,905 t f.e./year, while the total costs calculated by the objective function are equal to 50.5 million rubles/year.

In addition, the average cost of heat production at coal-fired boiler houses was calculated using only wood fuels (wood chips and pellets) in the republic. The value for this case is 897 rubles/Gcal. If coal is used in boiler houses in the same territory, the calculations showed that in this case the average cost of heat production is significantly higher and is equal to 1,584 rubles/Gcal.
4. Conclusion
The problem of engineering renewable fuels for the heat supply system of the region has been solved in order to maintain a balance in regional ecological systems. A mathematical model has been developed, which, in terms of the averaged values of raw materials reserves and fuel requirements, allows determining the optimal number of enterprises for the production of each type of fuel. The final mathematical relationships are obtained and the calculation of the optimal parameters for the location of enterprises for the production of wood fuels for supplying them to the distributed heat supply system of the region is carried out. Numerical calculations are given for the example of the Udmurt Republic. It is shown that the use of renewable wood fuels in the energy complex of the region is economically feasible.

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