Efficiency of using timber processing waste for heat supply of the city of Baikalsk

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Abstract. The heat supply problem of the city of Baikalsk is considered. The most environmentally friendly solution of this problem is using of the timber, which was felled during forest sanitation outside the Anchuk village. Environmental friendliness and other advantages of the biofuel are the main reason of using this type of heat source. This article presents comparative analysis of the production and delivery costs of the fuel wood chips and pellets for Baikalsk. Pressed fuel wood chips and chips with standard bulk density are considered. The levelized cost of heat, unit cost and capital costs are used as indicators of the economic efficiency of pellets and fuel wood chips. According to the results of all three economic indicators, pressed fuel chips proved to be most effective type of heat source than others. Unit cost and LCOH are roughly the same for pellets and for pressed fuel chips. However, the capital costs of production and transportation of the pellets are almost 50% higher than for pressed chips. Thereby, it is preferable to choose pressed fuel wood chips burning for economic reasons of the reducing transportation expenses.

1. Introduction

The heat supply problem of Baikalsk is discussed since 2013 when Baikalsk Pulp and Paper Mill (BPPM) was closed. Steam boilers type BKZ-75 which are installed at the Combined Heat and Power (CHP) plant were intended to provide steam to the technological processes of (BPPM) and for heating the city. Nowadays, the source of heat supply for the city is the Baikalsk CHP plant. After the closure of BPPM, the capacity of the steam boilers became redundant. The loads heating and hot water supply of the city are below the threshold for effective regulation of boilers, leading to excessive fuel consumption. Moreover, equipment of the CHP is worn out.

According to the contemporary environmental restrictions near Lake Baikal, replacement of the existing boilers with similar coal-fired boilers is not permissible.

Therefore, alternate reconstruction of heat supply sources for Baikalsk have been discussed over a period of 15 years. One of the possible options can be conversion of all boilers or several ones to biofuel [1].

Using biofuel is a relevant and perspective problem for small and medium settlements of the Eastern Siberia [2]. One of the important factors is the presence of the significant amounts of felling residues, timber processing and agricultural waste. It is necessary for heating suppliers of the
settlements, located in the Central Ecological Zone, to be environmentally friendly [2, 3]. The following kinds of biofuel satisfy this requirement:

- forest product residues;
- third-party pellets;
- timber, subject to sanitary felling.

Considering biofuel, it’s important to note that it has a relatively low energy density and its transportation over long distances significantly increases the final cost. So it is more rational to consider only those resources of biofuels which are available in sufficient quantities within the zone of the Baikalsk urban settlement.

2. Models and methods
LCOH, cost of production per unit and capital costs, which are necessary for the production and transportation of biofuels, are used as estimated indicators for evaluation of the economic efficiency of the pellets and the fuel wood chips as the energy sources for heat supply of Baikalsk.

According to the worldwide experience, levelized cost of energy (LCOE) is used as main instrument of selecting one energy project among several alternatives [4, 5].

This indicator is a ratio of the sum of all expenses during the project life cycle to the generated electricity. The LCOE indicator reflects such a tariff for heat energy at which the investor is provided with a break-even. One of the modifications of this ratio is LCOH [6], which can be calculated by the formula

\[
LCOH_j = \frac{\sum_{t=1}^{n} \frac{C(t)_j + I(t)_j}{(1+r)^t}}{\sum_{t=1}^{n} \frac{H(t)_j}{(1+r)^t}}.
\]

Here \(C(t)_j\) – project operating costs \(j\) per year \(t\), million rubles; \(I(t)_j\) – capital costs \(j\) per year \(t\), million rubles; \(r\) – discount rate; \(H(t)_j\) – the amount of heat produced per year \(t\), Gcal; \(n\) – life cycle of technology, number of years.

Overnight Capital Cost, which shows total investment excluding interest on loans, inflation, etc., is used to compare capital costs. In addition, it is important to use the unit cost of heat energy [7].

3. Results and discussion
Th wood from the territory subject to sanitary felling near the village of Anchuk, 65 km from Baikal, can be used for biofuel production. In the estimation of the Ministry of Forest Resources of Irkutsk oblast (2018), approximately 9.5 mln m³ of wood are concentrated within 65 km from Baikalsk. Assuming amounts of waste is approximately 40% of the initial raw timber, so, it will amount to 3.8 mln m³ of wood available for energy purposes. Net calorific value of wood waste at a moisture content of up to 40% is estimated at 2.05 Gcal/ton. Assuming the perspective annual heat energy consumption for heat supply of Baikalsk city is 300,000 Gcal/year and this consumption is entirely covered by wood waste, wood consumption would be 147,000 tons/year or 210,000 m³/year.

Such levels of consumption of the available wood reserves are enough to cover the perspective needs of Baikalsk for about 18 years. Considering that this resource is renewable, it can be assumed that the long-term potential of wood residual is sufficient. Also, it can be safely said that municipal solid waste will be used for energy purposes in the future.

According to a letter of the Ministry of Forestry of Irkutsk oblast of July 4, 2018, the cost of wood raw materials for biofuel production is 1125 RUB/m³. With an estimated raw material humidity of 40% and density is 0.63 tons/m³, the cost of the raw materials should be about RUB/ton.
3.1. Pellets production

Pellets are biofuels made from compressed organic matter or biomass. Its length is 20-50 mm, diameter is 4-10 mm, and 1 kg of wood pellets equals to 0.97 kg of coal and upon combustion forms 4.2 Mcal [8].

Pellet production technology includes several stages:
- crushing wood into large fractions by powerful comminuting devices;
- drying of semi-finished products in drier drums down to a moisture content of 8-12%;
- crushing wood pulp into sawdust by hammer mills;
- steam or water processing of crushed wood using screw mixers;
- pressing and cooling of pellet.

Many types of biomass, first of all, softwood contain lignin, which becomes a binding substance after heat treatment, so that additional binder additives are not required. In relation to Baikalsk, the use of pellets can be especially relevant due to the need of the lignin utilization. Stock of the lignin is estimated at up to 500 000 tons after the closure of the BPPM. Therefore, study into the feasibility of adding lignin to pellets is advisable.

Capital costs for the construction of the pellet plant include the following costs: construction costs of 2000 m² of a building with utility system; equipment costs for the wood chip preparation from logs (50×50 mm); cost of a technology line for the preparation and drying of chips in drums; pellet production line costs, including chopper and pellet-press; construction costs for a warehouse for storing biofuel; start-up costs. Taking into account high energy intensity of pellet production, it is advisable to install your own energy source – 2 MW mini-CHP. This can provide power supply for production at an estimated cost of electricity of 0.79 RUB/kW·h. It is necessary to purchase two wood chip trucks with a capacity of 60 m³ to deliver pellets from the place of production to Baikalsk.

Operating costs include costs of raw timber, electricity, fuels and lubricants, payroll (with a staff of 40 people), administrative expenses, amortization and tax.

All capital and operating costs for pellet production are summarized in the table 1.

Table 1. Capital and operating costs for wood pellets production for the heat supply of Baikalsk, considering the capacity of the plant of 87 000 tons per year.

| Item of expenditure                              | Costs, million RUB |
|------------------------------------------------|--------------------|
| **Capital costs**                               |                    |
| Building                                        | 50.0               |
| Equipment for the preparation of wood chips from logs (50×50 mm) | 30.0               |
| Equipment for the preparation and drying of chips in drums | 120.0              |
| Pellet production line, including mill and pellet-press | 160.0              |
| Mini-CHP (2 MW)                                 | 195.4              |
| Chip trucks                                     | 8.0                |
| Warehouses                                      | 8.0                |
| Installation                                    | 2                  |
| **Operating costs**                             |                    |
| Raw materials                                   | 221.0              |
| Electricity                                     | 17.2               |
| Fuels and lubricants                            | 7.0                |
| Payroll                                         | 19.2               |
| Administrative expenses                         | 20.0               |
| Amortisation                                    | 27.2               |
| Tax                                             | 6.0                |
Assuming the capacity of the plant is 87 000 tons pellets per year, total construction investments with cost of commissioning would be 573.4 mln RUB.

Taking into account all factors, production cost per unit would be 947.9 RUB/Gcal (or 3260.6 RUB/ton) and LCOH with 20 years project life and a discount rate of 10% is 1176.3 RUB/Gcal.

3.2. Fuel wood chips production
Compared with pellets, fuel wood chips have both advantages and disadvantages. On the one hand, capital costs and production costs of fuel wood chips are much lower than one’s of pellets. On the other hand, transportation of fuel wood chips over long distances is not economically feasible due to its low bulk density and combustion heat. Capital expenditures for the construction of a plant for the production of wood chips are 250.8 mln RUB. Compared to a pellet plant, there is no need for a pellet production line including a chopper and a pellet mill and press. Similar to pellet production it is advisable to set up a mini-CHP, but with a smaller capacity of about 1.5 MW. In addition, due to the larger volume of transported fuel wood chips, 9 chip carriers (trucks) are required. All capital and operating costs for fuel wood chips production are summarized in the table 2.

Table 2. Capital and operating costs for the fuel wood chips production for the heat supply of Baikalsk, considering the capacity of the plant of 153 000 tons per year.

| Item of expenditure                                      | Costs, mln RUB |
|----------------------------------------------------------|----------------|
| **Capital costs**                                        |                |
| Building                                                 | 50.0           |
| Equipment for the preparation of wood chips from logs 50×50 mm | 30.0           |
| Equipment for the preparation and drying of chips in drums | 120.0          |
| Mini-CHP (1.5MW)                                         | 146.5          |
| Chip trucks                                              | 36.0           |
| Warehouses                                               | 35.0           |
| Installation work                                        | 1              |
| **Operating costs**                                      |                |
| Raw materials                                            | 221.0          |
| Electricity                                              | 12.40          |
| Fuels and lubricants                                     | 30.7           |
| Payroll                                                  | 19.2           |
| Administrative expenses                                  | 18.0           |
| Amortisation                                             | 19.9           |
| Tax                                                      | 4.4            |

Capital investment in the construction of a plant for the production of fuel wood chips from logs with a capacity of 153 thousand tons/year is 418.5 mln RUB. Taking into account all factors, the unit cost would be 1004.2 RUB/Gcal (or 1963.3 RUB/ton), LCOH with a project life of 20 years and a discount rate of 10% – 1170.9 RUB/Gcal.

3.3. Pressed fuel wood chip production
In the production of fuel wood chips, the biofuel density is reduced by about 3 times compared to the density of the raw wood [9, 10]. Fuel wood chips can be compacted in two main ways. The first method is a more compact placement of chips without their significant deformation – «adjustment by shaking». Shaking is carried out due to vibration under the own weight of the chips. Due to vibration, a more compact placement of chips in the volume occurs. In this case, friction between the chips disappears and they move. The volume reduction is about 10%.
The second method is a combination of vibration exposure and gradually increasing pressure up to 0.1-0.5 MPa. Simultaneously with a more compact movement, the chips and their individual fragments are deformed without changing the structure (only by bending). The chips become flatter and fit more closely together. This is responsible for a more compact placement and volume reduction. The density of pressed chips approximates to the density of raw wood. The volume reduction is 50-67%.

The dependence of the chip compression force $p$ on the compression ratio can be approximated as follows:

$$p = C \exp \frac{k \Delta l}{l}.$$  \hfill (2)

Here $C$ – the constant that depends on the quality of fuel wood chips, MPa; $k$ – the compression coefficient; $l$ – the height of the fill, m; and $\Delta l$ is the fill height reduction. The $C$ and $k$ coefficients are determined empirically. In this case, taking into account the fact that under gravity (about 8 kPa (800 kgf/m$^2$) at the height of the fill of 4 m, the chip is compacted by about 10%, the values of the coefficients $C=4.2$ kPa and $k=2.26$ are accepted.

The energy consumption $E$ (kWh) for the compression is equal to

$$E = S \int_0^{\Delta l} p(x) dx,$$  \hfill (3)

Here $S$ is the fill area. Calculations show that compaction of a chip layer with an initial height of 4 m and an area of 1 m$^2$ to the height of 2 m requires an energy of 30.89 kJ (0.0086 kWh), without taking into account the efficiency of the device. To compress 60 m$^3$ of wood chips to 30 m$^3$, filled with a layer of 4 m with an area of 15 m$^2$, the force of 231 kN (23 t) and energy of 0.475 kWh (1.71 MJ) are required. For compaction from 120 m$^3$ to 60 m$^3$ the fuel wood chip layer should be lowered from 8 to 4 m. This will require an energy consumption of approximately 1.0 kWh.

Table 3. Capital and operating costs for the pressed fuel wood chips production for heat supply of Baikalsk, considering the capacity of the plant of 153,000 tons per year.

| Item of expenditure                              | Capital costs | Costs, million rubles |
|-------------------------------------------------|---------------|-----------------------|
| Building                                        | 50.0          |                       |
| Equipment (for the preparation of wood chips from logs 50×50 mm) | 30.0          |                       |
| Equipment for the preparation and drying of chips in drums | 120.0          |                       |
| Mini-CHP (1.5MW)                                | 146.5         |                       |
| Chip trucks                                     | 20.0          |                       |
| Warehouses                                      | 17.5          |                       |
| Press                                           | 3.0           |                       |
| Installation work                               | 1.2           |                       |
| Raw materials                                   | 221.0         |                       |
| Electricity                                     | 12.4          |                       |
| Fuels and lubricants                            | 15.3          |                       |
| Payroll                                         | 17.7          |                       |
| Administrative expenses                         | 16.0          |                       |
| Amortisation                                    | 18.4          |                       |
| Tax                                             | 4.1           |                       |
The simplest device for implementing the compaction process can be a removable steel plate with an area equal to the area of the wood chip truck body. Along the periphery of the plate, 6-8 screw jacks work through holes to compress the wood chip, each screw jack developing a force of 50-67 tons. It is advisable to place a vibrator on the plate to facilitate the pressing process. All capital and operating costs for pressed fuel wood chips production are summarized in the table 3.

The amount of necessary capital investment in the construction of a plant for the production of fuel wood chips from logs with a capacity of 153 thousand tons/year would be 388.2 mln RUB. Taking into account all factors, the unit cost of heat supply would be 941.4 RUB/Gcal (or 1840.6 RUB/ton). LCOH with a project life of 20 years and a discount rate of 10% would be 1096.1 RUB/Gcal.

4. Conclusion
Figure 1 shows the results of calculating indicators for the economic evaluation of the efficiency of pellets, fuel wood chips with a standard bulk density and pressed fuel wood chips.

![Comparison of costs for production and transportation of different fuels](image)

**Figure 1.** Comparison of different types of costs for production and transportation of pellets, fuel wood chips and pressed fuel wood chips.

Pressed fuel wood chips proved to be most effective in all three economic indicators considered (capital investment, LCOH and unit cost).

The unit cost and LCOH for pellets and fuel wood chips with a standard bulk density were approximately the same, but the capital costs required for the production and transportation of pellets are almost 25% higher than for fuel wood chips with a standard bulk density. Therefore, based on economic considerations, it would be preferable to choose the combustion of fuel wood chips with its preliminary pressing in order to reduce transport costs.

It is important to note that the lowest cost of heat energy for a consumer is achieved when using a mini-CHP plant operated on pressed fuel wood chips. Due to the production of relatively cheap electricity, the electricity cost for own needs of thermal power plants is reduced. It is possible to optimize the structure of heat sources, and transfer part of the heat supply facilities to electric heat sources, such as heat pump installations.
When using local biofuels, the reliability and stability of the heat supply system increases, and the dependence on a single supplier of energy resources decreases. The risks associated with an increase in railway fares are reduced.

The use of lignin in the pellet manufacture can increase the calorific value and strength of pellets and increase the available volume of biofuel resources. In addition, the problem of utilizing lignin accumulated in Baikalsk during the operation of Baikalsk Pulp and Paper Mill is partially solved. Since wood fuel is characterized by a closed carbon exchange (wood burning releases as much CO$_2$ as trees consumed during growth), we can assume that the emissions from wood combustion are zero. The use of environmentally friendly technology would increase the attractiveness of the city for business.

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