# Analysis of Energy Consumption in the Production Chain of Heat from Pellet

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**ABSTRACT**

Wood pellets, as a renewable energy source, are an alternative to fossil fuels. Their use contributes to the quantitative protection of the traditional energy resources which are non-renewable and single use. The combustion of pellets has a neutral effect on increasing the concentration of carbon dioxide in the atmosphere. An important environmental aspect of the Life Cycle Assessment of pellets is the energy consumption over its life cycle. The results of this assessment can be helpful in improving the environmental management in the companies related to the pellet life cycle. They can also be used in the comparative assessment of pellets and other energy carriers in terms of the environmental load resulting from the energy consumption over the entire life cycle of the analyzed fuels. The work aimed at analyzing and assessing the energy efficiency of using wood pellet taking into account its life cycle. In order to achieve the purpose of the work, the energy efficiency index, calculated as the quotient of energy benefits and energy expenditure incurred at individual stages of the pellet life cycle, was used. The results of the analysis indicate that among the studied stages of the pellet life cycle, the highest energy consumption occurs in the pellet use and production phases. Research shows that the energy benefits expressed in the amount of energy emitted in the form of heat in the pellet combustion process outweigh the energy expenditure being the sum of energy spent in subsequent stages of the pellet life cycle. The obtained results indicate a positive energy balance. The use of pellets for heating purposes allows for the recovery of energy spent throughout its entire life cycle.

**Keywords**: pellet heat production, pellet life cycle, energy consumption, energy efficiency, energy expenditure, energy benefits.

## INTRODUCTION

Wood pellets are processed solid biofuel, i.e. a renewable energy carrier. The basic materials for pellet production are sawdust and wood chips from sawmills and woodworking companies as well as the waste and residues from forestry. Biomass processing in the pellet production process improves its properties. In particular, in drying, the humidity of the pellet decreases, and in pressing, the energy density in the pellet increases. Low moisture content of pellet allows its even combustion, and this reduces the emission of pollutants from the combustion process.

The use of wood pellets as a substitute for fossil fuels has environmental benefits in terms of the $CO_2$ neutrality. This means that the biofuel combustion does not affect the intensification of the natural greenhouse effect. In addition, it helps to meet the requirements of sustainable development in the area of energy production.

An important environmental aspect of the Wood Pellet LCA (Life Cycle Assessment) test is the energy consumption in the pellet's life cycle. The results of this assessment can be helpful in improving the environmental management in the companies related to the pellet life cycle (including pellet production plants, transport and sawmills) in order to limit the adverse environmental impact of these entities. They can also be used in the comparative assessment of pellets and other energy carriers in terms of the environmental load resulting from the energy consumption over the entire life cycle of the analyzed fuels. The results

of this assessment may form the basis for making the decisions about promoting and co-financing the development of the energy carriers usage – the solutions that require the lowest energy expenditure should be supported.

The purpose of the work was to determine the energy input for energy purposes (production of usable heat /electricity) of wood pellets, taking into account the stages of the pellet life cycle and comparing the energy input with the amount of chemical energy contained in the pellet.

## PRODUCTION AND CONSUMPTION OF WOOD PELLETS IN THE EUROPEAN UNION

The consumption of wood pellets in the European Union (EU) in 2018 amounted to 27350 thousand t [4], with a production level of 16850 thousand t. The selected data regarding the wood pellet market in some EU countries are presented in Figure 1. A significant proportion of the use of wood pellets in EU is individual heating of residential buildings (40% of consumption in 2017). Other places where pellets are used are the industrial installations for the production of electricity and heat. There are different goals of pellet use in individual European countries. For example, in Germany, Italy and Austria, wood pellets, according to the GAIN report [4], are usually used for heating purposes in residential buildings and in medium-power industrial boilers. In the United Kingdom, the Netherlands and Belgium, the industrial use of wood pellets for electricity production is predominant.

In Poland, the production of wood pellets in 2018 amounted to 1100 thousand t, and consumption at the level of 350 thousand t. In comparison to the annual demand for pellets in Italy amounting to approx. 3800 thousand t, the pellet consumption in Poland is relatively low. The increase in the level of pellet use for heating residential houses in Poland may be affected by the financial support (from national and EU funds) of households for the installation of the pellet heating installations. A positive effect in this area can be ensured by the introduction (e.g. on a German model) of the obligation to use, at a defined level, renewable energy for the heating and cooling of new buildings. An element of the program of measures to increase the demand for pellets for heating purposes in domestic housing can also be the implementation of an economic instrument in the form of a $CO_2$ tax. Similar incentive solutions are needed in industry, especially in power plants, to increase the energy use of solid wood and agricultural biomass. The industrial use of biomass requires investments in the biomass power plants as well as combined heat and power plants or for the adaptation of heating systems in the existing biomass combustion/co-combustion plants.

In addition to the biomass in the form of wood pellets, wood chips and briquettes are also used in the EU. The consumption of briquettes and wood chips in the EU is estimated at 15–20 million tonnes [4].

## RESEARCH METHOD

It was assumed that the energy expenditure on the use of wood pellets is the sum of energy consumption at individual stages of the pellet life cycle (Fig. 2).
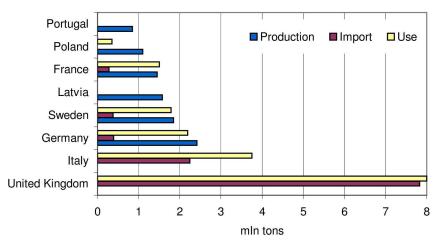


**Fig. 1.** Data regarding the wood pellet market in some EU countries (source: own elaboration, based on [4])
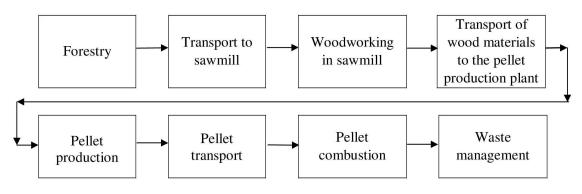
**Fig. 2.** Block diagram of the stages of the wood pellet life cycle

The reference (functional) unit was 1 kg of pellet. The values of the analyzed parameters will be converted into the functional unit (*fu*). The specific energy demand ($C_{ej}$) for the use of pellets is defined as follows:

$$C_{ej} = C_{ej,f} + C_{ej,tr1} + C_{ej,s} + C_{ej,tr2} +$$
$$+ C_{ej,p} + C_{ej,tr3} + C_{ej,c} + C_{ej,w} \tag{1}$$

where: $C_{ej,f}$ – energy consumption at the forest breeding stage

$C_{ej,tr1}$ – energy consumption for transporting round wood to the sawmill

$C_{ej,s}$ – energy consumption in the woodworking process in the sawmill

$C_{ej,tr2}$ – energy consumption for transporting the wood materials to the pellet production plant

$C_{ej,p}$ – energy consumption in the pellet production process

$C_{ej,tr3}$ – energy consumption for the pellet transport to the energy processing site

$C_{ej,c}$ – energy consumption in the pellet combustion process

$C_{ej,w}$ – energy consumption for waste management from the pellet combustion process

The sources of energy in the pellet life cycle are: electricity, liquid and gaseous fuels obtained from fossil fuels and biofuels. The value of the parameter ($C_{ej}$) allows for the calculation of energy efficiency index of the use of pellets ($E_e$) using the formula (2) [5, 6]:

$$E_e = \frac{B_e}{C_e} = \frac{Q_j}{C_{ej}} \tag{2}$$

where: $B_e$ – energy benefits from the use of pellets (of a given mass);

$C_e$ – energy expenditure on pellet use (of a mass);

$Q_j$ – calorific value of the pellet;

$C_{ej}$ – as in Eq. (1).

Energy benefits ($B_e$) is the potential amount of chemical energy contained in pellets, which is determined on the basis of the pellet calorific value.

The value of ($E_e$) index means the efficiency limit. The solutions for which the index value ($E_e$) is higher than one are effective, and when lower than one – inefficient. The absolute value of the difference between the indicator value ($E_e$) obtained from the calculations and the efficiency limit determines the level of effectiveness or inefficiency. The analyzed solutions are the more effective, the higher the values of the index ($E_e$) compared to the value of the limit efficiency. On the other hand, they are less effective if the values of the index ($E_e$) are lower than the efficiency limit.

In order to achieve the aim of the present work, the data from the review of environmental reports, statistical reports, LCA databases and scientific publications was used.

## ASSUMPTIONS AND RESEARCH RESULTS

It was assumed that 6.5 m³ of sawdust are needed to produce 1 t of pellet [1]. They are produced in sawmills in the process of round wood processing. It was considered that the main material for the production of pellet is softwood (Norway spruce or Scots pine). As a result of sawmill operations, 0.441 m³ of sawdust is generated from 1 m³ of round wood. Obtaining 1 t of pellets requires processing 14.74 m³ of wood. The sawdust parameters adopted for the purpose of calculations: bulk density 240 kg/m³, humidity 50%. The calorific value of pellet is equal to 17.4 MJ/kg indicates that 0.0575 kg of pellet are

needed to obtain 1 MJ of heat under complete combustion conditions.

The energy consumption at the stage of obtaining the wood material for pellet production depends on the energy consumption of subsequent phases of tree cultivation for the needs of the wood industry.

Tree breeding includes the preparation of seedlings, soil preparation for trees, tree planting, care works (removal of undesirable plants, trimming trees, fertilization or irrigation), felling and transport of trees from the felling sites to a storage yard located on the edge of the forest, from where they will then be transported to the wood products factories. At this stage of the pellet life cycle, electricity (for growing seedlings, protective measures), diesel, gasoline, kerosene (for tractors, trucks, agricultural aircraft) are consumed. The consumption of energy carriers by machinery and equipment depends on their power, the intensity of its use and compliance with the emission standards. According to research [1], the total energy consumption in forest cultivation is 155.4 MJ/m$^3$ wood (including $9.17 \cdot 10^{-5}$ MWh of electricity), which corresponds to 2.290 MJ/fu.

When transporting wood from the forest to the sawmill, fuels are used to drive motor vehicles and vehicle combinations. The amount of transport fuel consumed depends on the transport distance, the design of the vehicle engines that meet the specified exhaust emission standard (Euro), the type of road and the vehicle load. It was assumed that lorry trailers with a permissible total weight of 40 t and a load capacity of 26 t will be used for road transport of round wood from the forest. The calculation of energy consumption in round wood transport used the indicators of specific energy

consumption published by a Swedish organization NTM (Network for Transport Measures), shown in Table 1. These are the baseline levels of energy consumption that characterize the road transport in general in the EU. The energy consumption indicator (Table 1) applies to the entire fuel life cycle (diesel) – it covers the extraction, production, distribution and combustion of fuel in a vehicle. The calculations took into account the bulk density of freshly cut trees with a value of 775 kg/m$^3$ and their moisture content of 70%, and a transport distance of 80 km. Table 2 presents the results of the consumption of energy carriers for transporting round wood to the sawmill.

The technological operations carried out at the sawmill (including cutting, machining, milling, drying) are aimed at producing commercial wood products. The sawmill consumes heat (in the drying of wood products) and electricity (to power machines and technical devices). The by-products with high energy potential, such as sawdust, bark, chips and wood chips, are also produced during woodworking. For further considerations, it was assumed that only sawdust and bark will be used in the pellet production process – sawdust as a wood material, and bark as a biofuel in the sawdust drying operation and for the production of steam used for pellet pelleting. The bark consumption was assumed to be 0.001 m$^3$/fu, and sawdust consumption – 0.0065 m$^3$/fu.

Concerning the purpose of the work, it is necessary to determine the energy consumption in the sawmill for sawdust and bark. Table 3 summarizes the product quantities and energy consumption at the entry and exit of the sawmill production process, respectively. The values in Table 3 were determined on the basis of the data

**Table 1.** Energy consumption ratios for round wood transport to sawmill [7]

| Type of vehicle | Load index [%] | Emission norm Euro | Energy use index | |
|---|---|---|---|---|
| | | | [MJ/km] | [MJ/(t·km)] |
| Truck with trailer 34-40 t | 100 | V | 17.5 | 0.673 [1)] |
| | 50 | | 13.4 | 1.031 [1)] |
| Rigid truck 20-26 t | 100 | IV | 13.6 | 1.236 [2)] |
| | 50 | | 10.4 | 1.9 [2)] |

[1)] load capacity 26 t; [2)] load capacity 11 t.

**Table 2.** Data and results of energy consumption calculations for the transport of wood material to the sawmill

| Product | Wood bulk density [kg/m$^3$] | Distance [km] | Vehicle load index [%] | Energy use (in diesel oil) | |
|---|---|---|---|---|---|
| | | | | [MJ/m$^3$ wood] | [MJ/fu] |
| Round wood | 775 | 80 | 100 | 41.726 | 0.615 |

from sawmill installations [1]. The energy consumption is expressed per unit volume of sawdust obtained and per unit mass of pellet. Unit indicators of the quantity of individual sawmill products are given in $m^3/m^3$ sawdust. The quantities of individual sawmill products were also illustrated by means of a unit consumption indicator per ton of pellet. The distribution of energy consumption for each of the sawmill products was based on the economic value of these products and literature data [1]. The energy consumption allocated to the wood products (commercial and by-products) from the sawmill is shown in Table 4.

The data contained in Tables 3 and 4 show that 0.008 kWh/fu of electricity is used for bark at 0.001 $m^3$/fu, 0.212 MJ/fu for non-renewable energy carriers, and 0.098 MJ/fu for biofuels. The total allocation of energy consumption for sawdust and bark: electricity consumption – 0.057 kWh/fu, consumption of non-renewable energy carriers

– 1.474 MJ/fu and renewable energy consumption – 0.679 MJ/fu. The total energy consumption allocated to sawdust and bark is 2.358 MJ/fu.

The energy consumption for transporting the wood materials from the sawmill to the pellet production plant is directly proportional to the transport performance of the means of transport. It was assumed that sawdust and bark will be imported into the pellet production plant, with 6.5 times more sawdust by volume than bark, unit consumption of sawdust and bark with a value of 6.5 $m^3$/t pellet and 1 $m^3$/t pellet, respectively, volumetric densities: sawdust 0.24 $t/m^3$, bark 0.32 $t/m^3$, transport distance 100 km, the value of the indicator of energy consumption by heavy goods vehicles 0.673 MJ/(t·km) (Table 1). Considering the data above, the energy consumption for transporting the wood materials from the sawmill to the pellet production plant is 0.1265 MJ/fu.

In the pellet production plant, wood material (sawdust) is processed, including such technological operations as drying, milling and granulating. In turn, the produced pellets are subjected to cooling.

Wet sawdust contains 50–55% water [1], and the required water content in the production wood material reaches up to 10% [7]. In order to meet the requirements, the wood material is dried. Typical ones include tumble driers with direct heating of the wood material. The drying agent for sawdust is a stream of hot air with flue gases. The drying gases often come from biomass combustion in the form of bark and wood chips. In addition, tumble dryers with indirect material heating are employed, which use the heat from the air heated from a hot exchanger or steam. In modern production lines, belt driers are used, in which hot air is the heating factor. In the belt dryer of the Stelmet S.A. production plant (one of the largest pellet plants in Poland), the drying temperature is 100°C, which eliminates combustion of the wood material and destruction of the binder.

The aim of milling is to obtain the required degree of grinding and size homogeneity of the wood material (wood particles) for pellets. Hammer mills are used for this operation.

**Table 3.** Input and output components in sawmill production (based on [1])

| Item | Unit | Value |
|---|---|---|
| *Input* | | |
| Round wood | $m^3/m^3$ sawdust | 2.27 |
| | $m^3$/t pellet | 14.74 |
| Electric energy used | kWh/$m^3$ sawdust | 68.20 |
| | kWh/t pellet | 443.29 |
| Non-renewable energy used | MJ/$m^3$ sawdust | 1747.90 |
| | MJ/t pellet | 11361.29 |
| Biofuel used | MJ/$m^3$ sawdust | 805.48 |
| | MJ/t pellet | 5235.53 |
| *Output* | | |
| Plank | $m^3/m^3$ sawdust | 1.08 |
| | $m^3$/t pellet | 7 |
| Wood pulp | $m^3/m^3$ sawdust | 1.88 |
| | $m^3$/t pellet | 12.23 |
| Sawdust | $m^3/m^3$ sawdust | 1 |
| | $m^3$/t pellet | 6.5 |
| Bark | $m^3/m^3$ sawdust | 0.57 |
| | $m^3$/t pellet | 3.71 |
| Wood chips | $m^3/m^3$ sawdust | 0.36 |
| | $m^3$/t pellet | 2.34 |

**Table 4.** Allocation of energy consumption in sawmill products (based on [1])

| Item | Unit | Plank | Wood pulp | Sawdust | Bark | Wood chips |
|---|---|---|---|---|---|---|
| Electric energy used | kWh/fu | 0.172 | 0.178 | 0.049 | 0.031 | 0.013 |
| Non-renewable energy used | MJ/fu | 4.417 | 4.552 | 1.262 | 0.785 | 0.345 |
| Biofuel used | MJ/fu | 2.036 | 2.098 | 0.582 | 0.362 | 0.159 |

Properly dried and homogeneous wood material is subject to granulation in presses. Before entering the matrices, the wood material is mixed with 1–2% water in the form of water vapor – as a result, it softens and warms up to ca. 70°C [8]. Such conditions favor the release of lignins and the joining of wood particles into granules. Most often, ring matrices are used in the granulation technique, which can be rotary or flat. The wood material is pressed through rollers through the matrix holes, and then the pieces of granulated material are cut off with knives. Due to friction, when the wood mass is pressed through the matrix, its temperature increases (up to 150°C). A properly selected pressure value exerted by the press rollers ensures the correct course of the pressing process and the durability of the pellet.

Cooling the produced pellet to ambient temperature is aimed at removing the moisture from it (appearing in the pelleting phase) and increasing the durability of the pellet. This translates into a reduction in the amount of dust generated during the transport and storage of the cooled pellets. It is most often implemented in countercurrent coolers, in which the stream of cooling air flows in the opposite direction to the direction of pellet movement.

The pellets cooled to the required temperature are screened to remove small uncompressed wood particles. These particles have an adverse effect on the quality of the pellet, because they absorb water, which promotes the development of fungi and an increase in the temperature in the stored pellet. In addition, they increase the emission of nitrogen oxides from the pellet combustion process [2, 9]. The sieved fraction is recycled to the pellet production process.

In order to carry out the pellet production process, cyclone separators are also needed; they are used to clean both the gas drying the pellet wood material and the pellet cooling air.

The produced pellets are subject to packaging and storage. In internal pellet transport, mainly forklifts with combustion or electric drive are used.

Electricity is used to power the machines and devices needed in the pellet production process. Specialized machines and devices with electric drive are used, among others during drying, milling and transporting wood materials, as well as granulating, cooling and transporting pellets. Energy carriers in the form of fossil fuels are consumed by means of transport with combustion drive.

The enterprises producing pellets diversify the production capacity, e.g. Stelmet S.A. reaches a production capacity of 144000 t/year. Table 5 shows the consumption of wood materials, electricity and diesel oil in a company producing pellets with a capacity of 90000 t/year [1]. In addition, the value of the index of unit consumption of materials and energy per ton of pellets produced was given. Coniferous sawdust is used as wood material and bark as biofuel for the production purposes in this company. The technological line includes a drum dryer, a hammer mill, a granulating press with an annular matrix, a cold room for pellet cooling, a pellet screen and cyclone separators for cleaning sawdust drying gases and pellet cooling air. Diesel forklifts meeting the Euro 2 and Euro 3 emission standards are used in reloading works in warehouse halls.

Assuming a calorific value of 8.2 MJ/kg and a bulk density of 320 kg/m$^3$ for the bark, the bark consumption index in energy units was calculated at 2.624 MJ/fu. For the data: calorific value of diesel oil is 36 MJ/dm$^3$, oil density 0.84 kg/dm$^3$, the diesel oil consumption in the pellet producing company was calculated at 0.0324 MJ/fu. The electricity consumption is 0.583 MJ/fu. The consumption of energy carriers and electricity in the pellet production process is a total of 3.24 MJ/fu.

The energy consumption in the transport of pellets from the pellet plant to the place of its use was determined based on the assumptions: road transport using trucks with a trailer with a

**Table 5.** Consumption of wood materials and energy in an enterprise producing pellets (based on [1])

| Parameter | Unit | Value |
|---|---|---|
| Pellet production | t/year | 90000 |
| | t/t pellet | 1 |
| Sawdust use | m$^3$/year | 585000 |
| | m$^3$/t pellet | 6.5 |
| Bark use | m$^3$/year | 90000 |
| | m$^3$/t pellet | 1 |
| Electricity consumption | kWh/year | 14580000 |
| | kWh/t pellet | 162 |
| Diesel oil consumption | m$^3$/year | 81 |
| | m$^3$/t pellet | 0.0009 |

permissible total weight of 40 t and a permissible load capacity of 26 t, transport distance 165 km. The energy consumption in transport was calculated using the formula (3):

$$C_{ej,tr3} = W_{ze} \cdot P \qquad (3)$$

where: $W_{ze}$ – energy consumption indicator for means of transport, MJ/(t·km);

$P$ – transport distance, km.

For the assumed transport distance and the value of the ($W_{ze}$) indicator for the full load of vehicles (Table 1), energy consumption for the needs of pellet transport to its users is at the level of 0.111 MJ/fu.

In the use phase, the pellets are burned to produce heat – a secondary energy carrier. Heat is used to meet the thermal needs of buildings, both in terms of heating water and rooms. In addition, heat can be converted into electricity. The places where pellets are used can be divided, depending on the power of pellet burning devices, into large facilities (e.g. heat and power plants with a thermal power exceeding 2 MW), medium (e.g. heating plants with a thermal power from 50 kW to 2 MW) and small (detached houses and other facilities with a thermal power below 50 kW). The degree of utilization of the heating value of pellets depends on the thermal efficiency of the heating devices. Modern pellet boilers have a quite high thermal efficiency (approx. 85–91%) under nominal operating conditions [8]. Under real boiler operation conditions, when the nominal power is not fully used, the boiler efficiency is lower. The heat transfer losses also have a significant impact on the thermal efficiency of the municipal heating networks. The literature data shows that the thermal efficiency of the municipal heating networks is around 70%, and in less populated areas – even below this value. The demand for electricity at the stage of pellet combustion results from the power consumption of the heating installation, in particular through its components such as the electronic ignition system, pellet feeder, fan supplying air for combustion and control devices (optimizing the combustion process) and to control boiler operating parameters. Individual boiler designs can be differentiated by the level of electricity consumption.

The data below regarding the use of pellets in small combustion plants comes from the simulations of the pellet combustion process using the GEMIS 4.5 software (Global Emissions Model for Integrated Systems; 4.5 edition). The simulation parameters were selected so that the simulation results correspond to the combustion process in a typical 11 kW pellet boiler with a nominal thermal efficiency of 78%. According to the simulation results, the electricity consumption reaches 0.05 kWh/fu (0.18 MJ/fu), and the value of the unit pellet consumption indicator is 299.336 g/kWh heat. Comparison of the value of this indicator with the calorific value of the pellet 17.4 MJ/kg (206.897 g/kWh) shows that the boiler thermal efficiency for the simulation conditions is 69.1%. This means that 30.9% of energy is, lost as heat when burning a unit mass of pellets. The value of lost energy is 5.38 MJ/fu. It remains in the ash – in the form of unburned coal, while in the form of heat it penetrates into both waste gases and ash. Overall, in the pellet use phase, the energy consumption is 5.56 MJ/fu. This value constitutes 31.95% of the calorific value of the pellet, and 46.2% of the amount of heat released in the boiler.

As a result of burning pellets, waste is generated: combustion ash accumulating in the internal container in the boiler and fly ash retained in the waste gas purification devices. A certain amount of ash also comes from the cleaning of the combustion chamber and the pipes that remove gases from the combustion process. The amount and chemical composition of ash from pellet combustion depends on the type of wood materials used for pellet production [12]. The ash content in spruce with bark is 0.6% DM (dry matter) [3]. Therefore, the pellets from the coniferous sawdust are characterized by low ash content, approx. 0.5% by mass. (approx. 5 kg of ash from 1 ton of burned pellet) [10]. The composition of ash may be affected by the contamination of wood materials both in the pellet production process and during their transport or storage. The ash left after burning pure biofuel does not contain harmful components [11]. The increased amount of ash and the content of undesirable substances in it may indicate an increase in the pollution of the combusted biomass. The chemical composition of ash from wood pellet mainly contains mineral compounds (including $SiO_2$, CaO), small amounts of microelements (including copper, zinc, chromium, nickel, lead) and other substances formed at the stage of tree growth and in the remaining phases of the pellet production chain. The quantitative composition of ash depends on the properties of the biomass burned.

The higher the pellet quality, the lower the ash content. The pellets intended for retail may have a quality certificate – a document confirming the compliance of the pellets with the requirements of the relevant standards. The EU has an EN 14961-1÷6 standard. The second part of this standard (EN 14961-2) contains the requirements for the wood pellets. A pellet manufacturer that meets the parameters defined in the standard in class A1 can obtain a DINplus or ENPlus certificate. The ENPlus certificate in class A2 can be obtained by the pellets that meet the standard requirements for this class. The certificate logo indicates the certifying authority. For DINPlus, the certification supervisor is DIN CERTCO (German Institute for Standardization), and for ENPlus – European Pellet Associations. The A1 and A2 class pellets are differentiated by the dry ash limit content and for the class A1≤0.7%, for class A2≤1.5%. The Class A1 pellets are intended for central heating boilers with lower heat output, and Class A2 for the boilers with higher power. The pellets for industry belong to class B.

The producers of waste from the combustion of wood pellets are subject to the legal requirements in the field of waste management. The requirements set depend on the power of heating installations with biofuel boilers. The users of small heating installations (in individual houses and small boiler rooms, e.g. in public buildings) are subject to the guidelines contained in the regulations for maintaining clean communes. The wastes from the combustion of wood pellets in boilers of low-power heating systems are classified as municipal waste. Some municipal authorities allow this waste to be directed to the containers with mixed waste. Others, in turn, demand that this waste be collected separately. In addition, when treated as seasonal waste, it can be collected by specialized companies only during the heating period. Due to the chemical composition and fertilizing properties of ash from pellet, it is possible to use it to fertilize mineral soil.

Fuel combustion plants should classify the ash and dust from solid biomass combustion to the waste group no 10 (waste from thermal processes), subgroup 1001 (waste from power plants and other energy combustion plants). The above requirement also applies to local boiler houses using the wood fuel to generate the heat sold for the needs of central heating and hot water preparation in apartment blocks, schools, enterprises and other facilities, including service and administration. The furnace waste from these enterprises should be transferred to authorized entities based on the waste transfer card.

The energy input for waste management from solid biomass combustion in small heating installations is negligible or even zero when this waste, as a plant fertilizer, is scattered over the soil surface.

In large pellet combustion plants, the energy input for waste management depends on the fuel consumption per unit of transport work in the transport of waste to the landfill. With a small amount of waste and a short transport distance, the energy consumption for waste transport is insignificant. For the assumptions: the amount of combustion waste from large combustion plants with a value of 23.43 kg/fu [1], the distance of waste transport of 20 km, transport by truck with a maximum permissible weight of 24 t and load capacity of 11 t, fully utilized load capacity, unit consumption indicator energy by a vehicle with a value of 1.23 MJ/(t·km) (Table 1), the energy consumption for transporting the combustion waste to a landfill from large pellet combustion units, calculated according to the formula (3), is 0.576 MJ/fu.

Table 6 summarizes the results of calculations of energy expenditure on pellet use throughout its life cycle.

The energy efficiency index in the study, calculated on the basis of formulas 1-2, is:

$$E_e = \frac{17.4}{2.290 + 0.615 + 2,.58 + 0.127 + 3.240 + 0.111 + 5.560} = 1.217$$

The value of the index ($E_e$) is higher than the efficiency limit, so the use of wood pellets for energy purposes in small heating installations is reasonable and effective.

**Table 6.** Energy expenditure on the use of wood pellets in small heating installations

| Energy use per unit [MJ/fu] | | | | | | | |
|---|---|---|---|---|---|---|---|
| Forestry | Transport to sawmill | Woodworking in sawmill | Transport to the pellet production plant | Pellet production | Pellet transport | Pellet combustion | Waste management |
| $N_j$ | $N_{t1j}$ | $N_{sj}$ | $N_{t2j}$ | $N_{pj}$ | $N_{t3j}$ | $N_{cj}$ | $N_{wj}$ |
| 2.290 | 0.615 | 2.358 | 0.127 | 3.24 | 0.111 | 5.56 | - |

## CONCLUSIONS

The efficiency indicator adopted in the study enables to determine the energy and environmental benefits of using wood pellets for heat production. The efficiency ratio and energy value of the pellets are proportional. In turn, the relationship between the efficiency indicator and energy expenditure in subsequent stages of the pellet life cycle is inversely proportional.

The results of the analysis indicate that among the studied stages of the pellet life cycle, the highest energy consumption occurs successively in the phases: pellet use and production. The high energy consumption during the pellet use phase is affected by the large amount of energy lost, which is emitted as heat when the pellet is burnt. The amount of energy lost depends on the thermal efficiency of the combustion installation.

The research shows that the energy benefits expressed in the amount of energy emitted in the form of heat in the pellet combustion process outweigh the energy expenditure being the sum of the energy spent in subsequent stages of the pellet life cycle. The obtained results indicate a positive energy balance – 1.217 MJ of energy is obtained from 1 MJ of energy spent for the production and use of pellets. The use of pellets for heating purposes allows for the recovery of energy spent throughout its entire life cycle.

Wood pellets, as a renewable energy source, are still needed by the national power industry an alternative to fossil fuels. When used as a substitute for fossil fuels, it can reduce their consumption and decarbonize, especially the heat energy. Lower consumption of fossil fuels also means lower environmental burden of the emissions from the combustion installations of these fuels and, as a result, greater economic and human health benefits. Replacing the energy of fossil fuels with any form of renewable energy is a way of quantitative protection of non-renewable energy sources, the existence of which in the environment determines the sustainable social and economic development. In order for the pellet market to reach an appropriate level of development, it should be financially supported by means of subsidies and other economic incentives.

On the basis of the energy efficiency index presented in the paper, it is possible to conduct a study on the impact on the energy consumption of selected factors, including the changes in the area of transport (e.g. use of low-emission means of transport) or technical parameters of the pellet combustion installations. The test results can then be used to compare different pellet heating installations and transport solutions for energy consumption throughout the pellet lifecycle.

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