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Operational Analysis and Optimization of a District Heating Plant Using Wood Chips

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Abstract: The transition from outdated biomass boiler systems to modern, efficient district heating technologies represents a critical pathway toward sustainable energy production. In this study, the replacement of obsolete solid biomass-fueled boilers with a new wood chip-based heating system in the district heating plant of Pale, Bosnia and Herzegovina, was analyzed under real-world operational conditions. Historical operational data, including annual fuel consumption, were obtained directly from the facility. The degree-day method was applied to evaluate the thermal efficiency of the former heating system and to estimate the annual fuel demand for the newly installed wood chip-based infrastructure. A key component of this transition involves the reliability and efficiency of the wood chip supply chain. Therefore, the logistical feasibility of securing a continuous, local, and renewable wood chip fuel source was examined, including the assessment of storage capacity and supply chain resilience. Furthermore, a scenario-based simulation was conducted to project the cost of heat production under varying fuel price conditions and market dynamics. Through this integrated approach, a replicable methodology was proposed for replacing legacy biomass heating systems with environmentally sustainable, economically viable district heating technologies based on locally sourced wood chips. The findings offer a practical roadmap for municipalities aiming to achieve energy transition targets through the adoption of locally available renewable energy sources, with particular emphasis on operational feasibility, fuel logistics, and cost-effectiveness.

Keywords: Heating plant; Wood chips; Logistics; Optimization; Supply chains; Renewable energy

1 Introduction

Densely populated urban areas are ideal locations for the implementation of district heating systems. Through the application of energy efficiency measures and the use of renewable energy sources, district heating systems within local communities can become part of sustainable solutions in the processes of global energy transition [1]. Modeling district heating systems and thermal energy distribution networks in combination with various renewable energy sources presents a challenge in terms of achieving improved system efficiency [2]. In this regard, various scenarios have been developed concerning primary energy savings and reduced CO_2 emissions, and economic indicators have been calculated for such systems [3]. Centralized heat production systems are considered a key technology for increasing energy efficiency [4], replacing less efficient, often individual systems [5]. In addition, these systems do not face issues related to fuel storage in urban areas. Some life cycle assessment (LCA) studies on district heating show that such systems could significantly contribute to the decarbonization of energy in the building sector [5]. There are different approaches to planning and retrofitting heating systems for residential buildings. One such project is HARP, or Heating Appliances Retrofit Planning, which aims to motivate individuals to plan the replacement of their often outdated and fossil-fuel-operated heating appliances with more efficient alternatives [6]. In this context, this study also focuses on replacing old solid fuel boilers using wood biomass with wood chip boilers, aiming to supply thermal energy to the municipality of Pale through a district heating system. Wood chips mainly come from by-products of forest management [7] and wood processing plants. They belong to the solid wood-based biofuel [8].

This study aims to demonstrate a universal protocol in planning and using wood chips as fuel in a feasibility study for a real district heating plant in the municipality of Pale (Republic of Srpska, Bosnia and Herzegovina). In addition, several factors were considered in this study, including the logistics of the wood chip supply chain, the local availability of this resource as well as different scenarios and their impact on the feasibility of this plant in terms of the price of the produced heat energy.

2 Methodology

Data from the existing old heating plant in the municipality of Pale, Bosnia and Herzegovina, was used in this study [9]. In this regard, all necessary information about the existing biomass boilers, their fuel consumption, etc., was taken. Based on this data, an analysis of the efficiency of the existing system was also performed, as well as a calculation of the required amounts of fuel in the form of wood chips for the new planned district heating system. By taking into consideration both existing and new consumers, the required power of 10 MW was established for the wood chip boiler for the new district heating system. The degree-day methodology was used to estimate the required amounts of fuel [10]. Based on a survey of the amounts of wood residue from existing wood processing companies, as well as forestry companies engaged in the cultivation and exploitation of forests, it was found that it is possible to provide sufficient amounts of wood chips as fuel for the new heating plant [11]. In addition to the planned procurement costs for the wood chip boiler, the costs of reconstructing the existing district heating network and equipment were also planned. The options for supplying wood chips as fuel were analyzed, and their multi-criteria optimization was performed using the VIKOR-entropy method [12–14]. With the help of developed calculation models in Excel and by using the Dignet Energy Platform (DEP) [15], a model of a new heating plant was created, and various scenarios were developed regarding the prices of produced heat and the profitability of this heating plant. The following section presents the universal protocol in planning and using wood chips as fuel in a district heating plant at the municipality of Pale.

3 Basic Information on Heat Generation in the District Heating System

Two wood biomass boilers were installed in the district heating system in Pale. The first one has a capacity of 6.5 MW with a steam boiler with manually feeding fuels, and the second one has a capacity of 2 MW with a hot water boiler with automatically feeding fuels (wood chips). The approximate annual consumption of both boilers is about 27,000 bulked/stacked m^3, including wood chips, sawdust, shavings, bark, etc. Generally, an automatically fired boiler of 2 MW consumes about 3000 bulk m^3 of wood chips annually. The rest is consumed by the first steam boiler with 6.5 MW hand-feeding fuels [9].

The total quantity of fuel procurement items in 2022 for the heating plant is 27000 bulk m^3 per year, which includes six parts as follows [9]:

Part 1: wood chips (fir, spruce) V_1=7500 bulk m^3;
Part 2: ground bark V_2=7500 bulk m^3;
Part 3: sawdust (fir, spruce) V_3=2000 bulk m^3;
Part 4: fir, spruce V_4=2000 stack m^3;
Part 5: sawdust (beech) V_5=6000 bulk m^3;
Part 6: large wood waste V_6=2000 stack m^3.

All of the amounts, converted into the heating value of the fuel with appropriate assumptions, are equal to the following calculation by Eq. (1):

Part 1: wood chips, mainly fir

$$\begin{aligned} Q_1 &= V_1 \cdot C_f \cdot 10^3 \cdot \frac{LHV_c \cdot (100-w) - (2.44 \cdot w)}{100} \\ &= \frac{7500}{3} \cdot 10^3 \cdot \frac{19.49 \cdot (100-50) - (2.44 \cdot w)}{100} \\ &= 21321 GJ \end{aligned} \tag{1}$$

Part 2: wood chips from bark, wood, and conifers

$$Q_2 = \frac{7500}{4.6} \cdot 10^3 \cdot \frac{19.49 \cdot (100-50) - (2.44 \cdot w)}{100} = 13899 GJ$$

Part 3: sawdust (fir, spruce)

$$Q_3 = \frac{2000}{5.7} \cdot 10^3 \cdot \frac{19.49 \cdot (100-50) - (2.44 \cdot w)}{100} = 2990 GJ$$

Part 4: fir, spruce, and Part 6: large wood waste totaling 4000 stack m^3. This is the sum of Part 4 and Part 6. The assumption is that these two parts have the same bulk density and conversion factor CF, see Table 1. Therefore, the same formula and the sum V_4+V_6 are used.

$$Q_4 = \frac{4000}{3} \cdot 10^3 \cdot \frac{19.49 \cdot (100 - 50) - (2.44 \cdot w)}{100} = 11366GJ$$

Part 5: sawdust (beech)

$$Q_5 = \frac{6000}{3.6} \cdot 10^3 \cdot \frac{18.82 \cdot (100 - 50) - (2.44 \cdot w)}{100} = 13630GJ$$

The total estimated lower heating value (LHV) of the fuel is approximately $Qs = 63200$GJ or 17555 MWh per year. This assessment was calculated with the following assumptions: LHV for conifers for completely dry wood $LHVc = 19.49\mathrm{MJ/kg}$, LHV for beech for completely dry wood $LHVb = 18.82\mathrm{MJ/kg}$, moisture in the fuel $w =$ 50%, density of wet wood for conifers $\rho_c = 833.33\ \mathrm{kg/m^3}$, density of wet wood for beech $\rho_b = 1333.33\ \mathrm{kg/m^3}$, and density for wet bark $\rho_{ba} = 260\ \mathrm{kg/m^3}$ [16]. Conversion factors for 1 m^3 bulk or stacked wood residues into mass units (tons) are presented in Table 1.

Table 1. Test results of classification

Volume Measure	**Type of Wood Residue**	**Solid Volume Fraction (SVF) [16, 17]**	**Conversion Factor (CF) in tons, w = 50%**
1 m^3 bulk	Wood chips (fir, spruce)	0.4	1/3
1 m^3 bulk	Wood chips from bark + wood	0.4	1/4.6
1 m^3 bulk	Sawdust (fir, spruce)	0.21	1/5.7
1 m^3 bulk	Sawdust (beech)	0.21	1/3.6
1 m^3 stack	Pieces of wood stacked (fir, spruce)	0.4	1/3

The total consumption of different categories of wood fuel is equal to about 7500 tons in the heating plant per year. In the redistribution, about 3000 m^3 of bulk wood chips are consumed by the 2 MW boiler [9], while the 6.5 MW boiler consumes the rest. In the calculation, amounts of 1000 tons per year correspond to the consumption in 2 MW boiler, and the rest of 6500 tons for a 6.5 MW boiler. The value of moisture in the fuel was taken to be around 50% (conservative assumption).

a) First boiler (6.5 MW)

According to the degree-day method [10], the degree of efficiency of both boilers was checked according to the data obtained from the heating plant by Eq. (2):

$$B = \frac{24 \cdot 3.6 \cdot e \cdot y \cdot SD \cdot Q}{(tu - ts) \cdot Hd \cdot \eta} \tag{2}$$

For a boiler with 6.5 MW capacity, the energy efficiency was calculated by Eq. (3):

$$\eta = \frac{24 \cdot 3.6 \cdot e \cdot y \cdot SD \cdot Q}{(tu - ts) \cdot Hd \cdot B \cdot 1000} = 0.49 \tag{3}$$

where, the following assumptions were applied [10]:

$e = e_t \cdot e_b = 1 \cdot 1 = 1$

$e_t = 1$ (temperature limitation coefficient)

$e_b = 1$ (exploitation limit coefficient)

$y = 0.6$ (correction factor, normally windy areas, open position)

$SD = 3077$ (number of heating degrees-days for pale)

$Q_p \approx 6.5\mathrm{MW}$ (boiler heat capacity)

$t_u = 20°\mathrm{C}$ (indoor project temperature)

$B = 6500$ tons per year

$t_s = -18°\mathrm{C}$ (outdoor project temperature)

$Hd = 8.525\ \mathrm{kJ/kg}$ (LHV for wood fuels with 50% moisture)

This represents a very low level of energy efficiency of the existing observed heat production system.

b) Second boiler (2 MW)

This boiler with 2 MW heat capacity, which was installed in 2015, was fueled by wood chips, and its coefficient of efficiency ranged from 0.81 to 0.9, depending on the quality of the chips. It represents an efficient system for heat production.

c) Biomass needs for the new 10 MW boiler on wood chips

The annual fuel consumption for 10 MW of heat generation capacity for the new boiler (fresh wood chips, mostly conifers) [10] was calculated by Eq. (4):

$$B = \frac{24 \cdot 3.6 \cdot e \cdot y \cdot SD \cdot Q}{(tu - ts) \cdot Hd \cdot \eta} = 5500tons \tag{4}$$

where, the following assumptions were applied [10]:

$e = e_t \cdot e_b = 1 \cdot 1 = 1$

$e_t = 1$ (temperature limitation coefficient)

$e_b = 1$ (exploitation limit coefficient)

$y = 0.6$ (correction factor, normally windy areas, open position)

$SD = 3077$ (number of heating degrees-days for Pale)

$Q_p \approx 10\text{MW}$ (boiler heat capacity)

$t_u = 20°\text{C}$ (indoor project temperature)

$\eta = 0.9$ (energy efficiency of the new boiler)

$t_s = -18°\text{C}$ (outdoor project temperature)

$Hd = 8.525\text{KJ/kg}$ (for wood fuels with 50% moisture)

In general, if wood chips are fuel, then the amount of bulk m^3 of chips based on calculated tons can be estimated according to the conversion factor for wood chips, SVF = 0.4, and fresh wood chips (conifers) with moisture w = 50% (Table 1) and Eq. (5):

$$Vchips = \frac{B}{Cf} = \frac{5500}{0.3} = 16500\ m^3 \tag{5}$$

The estimation of wood consumption in cubic meters per year (mostly conifer) was calculated by Eq. (6):

$$V = Vchips \cdot SVF = 16500 \cdot 0.4 = 6600\ m^3 \tag{6}$$

In addition, it was converted into energy units of LHV per year, as shown in Eq. (7):

$$Q = \frac{B \cdot Hd \cdot 1000}{3600} = \frac{5500 \cdot 8.525 \cdot 1000}{3600} = 13024MWh \tag{7}$$

All the previous analysis was carried out to assess the real situation of the need for wood biomass (wood chips) for the new 10 MW heat capacity boiler in comparison with the current demand. The fuel consumption on an annual level (method of number of degrees-days) for the 10 MW boiler was calculated to obtain the annual realistic needs of fuel for the planned new heating plant.

4 Assessment of the Wood Residue Potential in the Sarajevo-Romanija Region

To assess the potential of wood biomass available for heat generation in the district heating system, meetings were held in the headquarters of Forestry Department of Jahorina (FDJ), Forestry Department of Romanija-Sokolac (FDR), and Departments of Public Enterprise Šume Republike Srpske (PESRS). These forestry departments manage state-owned forests on the territory of the municipalities of Pale, Sokolac, Han Pijesak, and Rogatica. PESRS holds the prestigious FSC® (FSC® C013091) certificate for forest management [11].

In addition, meetings and interviews with wood processing companies were organized. Very useful information on the potential for wood processing biomass and forest biomass was obtained. Wood waste generated in the territory of Pale, Sokolac, Han Pijesak, and Rogatica municipalities is considered available biomass for the district heating system in Pale. Distances between the towns of Pale, Sokolac, Han Pijesak, and Rogatica are less than 90 kilometers, representing acceptable distances for transporting wood residues for fuel.

One aspect of the assessment of the wood biomass potential of Pale, Sokolac, Han Pijesak and Rogatica municipalities includes only residues from sawmills. Use of low-quality wood as one of the scenarios was proposed in this study within the cooperation between District Heating Pale, the municipality of Pale, and FDJ.

The wood energy potential from the sawmill residues was assessed based on the following data and assumptions:

• The amount of available wood residue can be obtained by considering the distribution of wood processing capacities in the observed municipalities. Therefore, the observation of cut wood at the level of public forestry department companies is unusable information.

• The unused available potential for exploitation is 2/3 of the total forest cut residues because 1/3 has to be left in the forest. However, forest cut residues are not used because the forest management companies are not sure that this process would be performed sustainably.

• It is assumed that both conifers and deciduous forest residues have the same humidity (50%) and a heat value of 8.525 MJ/kg.

• The specific mass of dry conifers and dry deciduous forest residues is 450 kg/m^3 and 720 kg/m^3, respectively (per cubic meter).

The amount of sawmill waste was assessed based on the following data, assumptions, and procedures:

• Sawmill wood waste is generated only from primary wood processing.

• It is assumed that both conifers (mostly conifers) and deciduous forest residues (firewood is hardwood) have the same humidity (50%) and a heat value of 8.525 kJ/kg.

Respecting all the previous items, after conducting research and assessment of wood residues, it was concluded that the total available potential of wood biomass residues is Vr = 65500 m^3 (in bulk form) in the observed territory. Most of this wood residue is conifer. In this term, the assessment of the amount of heat energy stored in that fuel as LHV follows Eq. (8):

$$Qu = Vr \cdot SVF \cdot 1000 \cdot Hd = 65500 \cdot 0.33 \cdot 1000 \cdot 8.525 = 51185 MWh \tag{8}$$

It may be concluded that the annual potential of wood residues from wood processing companies in the territory of the Sarajevo-Romania region is approximately equal to 51185 MWh LHV of fuel. When taking a new heating plant (10 MW) with fuel needs on an annual level of Q = 13024 MWh, the ratio of total available fuel quantities (from wood processing residues) to the needs of the new plant can be obtained using Eq. (9):

$$n = \frac{Qu}{Q} = \frac{51185}{13024} = 3.9 \tag{9}$$

It can be concluded that the residues from wood processing and wood chip production (in the Sarajevo-Romanija region) can cover 3.9 times the fuel needs of the new heat generation plant with 10 MW of heat generation capacity.

4.1 Potential for Using Low-Quality Wood from the Local Forest Company

Certain amounts of low-quality wood from the category of cellulose, firewood, and coppice forests can be used for the production of wood chips and fueling a new boiler in the district heating. FDJ has expressed interest in delivering these categories of wood to the City Heating Plant in Pale in terms of quantities of Vw = (8000 to 10000 m^3) per year (full cubic meters) of the aforementioned types of wood biomass.

In that context, the assessment of additional amounts of energy contained in the delivered amount of low-quality wood in the form of LHVs per year is expressed by Eq. (10):

$$Qw = Vw \cdot \rho c \cdot Hd = 8000 \cdot 833,33 \cdot 8.525 = 15786 MWh \tag{10}$$

This estimate refers to coniferous wood with a moisture content of 50%. This option was also considered as one of the possibilities of supplying the heating plant with fuel. Taking into account this way of fuel supply as well as previously mentioned residues from wood processing, the amount of available fuel increases in relation to the needs of fuels for the heating plant to total ratio, as shown in Eq. (11):

$$n = \frac{Qu + Qw}{Q} = \frac{51185 + 15786}{13024} = 5.14 \tag{11}$$

In this case, the possibility of supplying the heating plant with fuel increases significantly, as well as some other positive effects presented in the next chapter related to biomass supply logistics.

5 Biomass Supply Logistics for a District Heating Plant

The logistics of supplying biomass as fuel are the most important part of any project of this type. For these reasons, special attention was paid in this report to that part. In order to secure enough biomass, the new district heating company with 10 MW installed heat capacity should:

a) Establish contracts (at least five years) with the local companies for wood chip production and supply (in the territory of Pale, Sokolac, Han Pijesak as well as neighboring municipalities).

b) Establish long-term contracts with FDJ and PESRS on collecting and taking out low-quality wood from the categories of cellulose, firewood, and coppice forests.

c) Provide covered seasonal storage for wood chips on a land area of about 25 m × 50 m (for a 10 MW plant) and a land area for the storage of about 7000 m^2.

d) Procure machines for the production of wood chips (wood chipper) and their manipulation and transport to the heating plant.

5.1 Seasonal Storage for Wood Chips

The capacity of that wood chip storage should be enough for a period of about two months because working conditions are bad in wintertime when the exploitation and processing of wood are reduced.

The planned seasonal storage for wood chips should meet the needs of at least the equivalent of 1.5 months of fresh stored fuel (wood chips) for the operation of the heating plant (10 MW) in the average mode of operation. This means that the amount of fuel needed for 1.5 months would be the value in Eq. (12):

$$Bm = \frac{B \cdot 1.5}{6} = \frac{5500 \cdot 1.5}{6} = 1375 tons \tag{12}$$

To express in volume unit m^3 for bulked wood chips, Eq. (13) is needed:

$$Vs = Bm \cdot 3 = 4200 m^3 \tag{13}$$

The dimensions of the wood chip storage with a sloping roof would be $Vs = 50 \cdot 25 \cdot 6 = 7500\ \mathrm{m}^3$. When taking the filling of the space storage at 60%, then it is possible to store $Vs = 4500\ \mathrm{m}^3$ of bulked wood chips. This value was adopted for further calculations. The height of piles for chips is not recommended to be higher than 3.5 m [18].

Taking the possibility of storing dried chips at about 30% moisture, i.e., $Hd(30\%) = 12\mathrm{MJ/kg}$, in the summer period in a seasonal storage, it is possible to store about the following amount by Eq. (14):

$$Q_s = V_s \cdot Cf \cdot 1000 \cdot \frac{Hd(30\%)}{3600} = \frac{4500}{3} \cdot 1000 \cdot \frac{12}{3600} = 5000 MWh \tag{14}$$

This corresponds to the ratio 13024/5000 = 2.6, which represents the equivalent of storage of about 2.5 months. This should be one of the first recommendations for the logistics of this plant. Figure 1 shows one possible form of storage for wood chips [19].

The approximate price of such storage construction is around 300 BAM per m^2 [20] of floor area. In that case, the investment in the storage hall (Is) is around $Is = a \times b \times 300 = 300 \times 50 \times 25 = 375000 \mathrm{BAM}$.

Figure 1. Wood chip storage facility at the Biomass Trade Centre Achental, Germany [19]

5.2 Fuel Supply Logistics

Three logistics scenarios of supplying wood chips as fuel for the 10 MW plant were considered as follows:

a) Procurement of wood chips from local suppliers in the region (only purchase of loader machine and wood chip truck and trailer depending on the location of the seasonal storage in relation to the heating plant).

b) Procurement of a medium-capacity class of wood chipper driven by tractor, wood splitter, loader machine and trailer for tractor for wood chip transport. This option is related to 50% produced wood chip fuel at seasonal storage using the purchased low-quality wood by FDJ. The shortfall in the amount of wood chips of about 50% would be bought at local market prices.

c) Procurement of a medium-capacity class of wood chipper driven by tractor, wood splitter, loader machine and trailer for tractor for wood chip transport. This option is related to the fully produced wood chip fuel at seasonal storage using the purchased low-quality wood by FDJ. All previously mentioned scenarios with their characteristics (criteria) are given in Table 2.

Table 2. Test results of classification

Options	Dependence on other wood chip suppliers (%), C1	Investment in logistics (BAM), C2	Price of wood chips (BAM per ton), C3
Scenario 1	100%	Truck + trailer + telescopic wheel loader $\approx 260000 + 100000 + 80000$ ≈ 440000	140
Scenario 2	50%	Medium capacity wood chipper driven by tractor, power range $(260 - 300\text{PS})$+wood splitter+ telescopic wheel loader machine + trailer for tractor $\approx 400000 + 450000 + 40000 + 80000 + 50000$ $\approx 1.020.000$	130
Scenario 3	0%	Medium capacity wood chipper driven by tractor, power range $(260 - 300\text{PS})$ + wood splitter + telescopic wheel loader machine + trailer for tractor $\approx 400000 + 450000 + 40000 + 80000 + 50000$ $\approx 1.020.000$	120

Information regarding wood chip processing equipment was obtained from the manufacturer JENZ through the supplier FOREST POWER. Consultation with technical experts was conducted to validate the suitability of the machinery for the proposed logistics chain. The recommended technical specifications for the chipper include a maximum hardwood diameter of 42 cm, a maximum softwood diameter of 56 cm, and an approximate maximum output of up to 140 m^3/h of bulk wood chips (in solid volume). The tractor required to operate the chipper should possess a power range between 260 and 300 PS [21].

Three categories of criteria were established for selecting the optimal variant of fuel supply for the new heating plant in Pale for a thermal capacity of 10 MW, namely dependence of the heating plant on the market and wood chip suppliers (C1), total investment in logistics (C2) and potential prices of wood chips (C3). It should be noted that the prices are a variable category and may deviate significantly from those listed in Table 2, especially equipment prices. All prices are presented exclusive of value-added tax (VAT). Table 3 shows more information on the prices of wood chips.

Three scenarios describe the possible cases for realizing the necessary logistics of supplying wood chips as fuel to the heating plant.

The first scenario is related to the option where there is no wood chipper, and all fuel, like wood chips, would be purchased from local suppliers. The logistics equipment that would be purchased in all scenarios is given in Table 2. This scenario is 100% dependent on the market prices of wood chips (C1 criteria).

The second scenario refers to the option to supply fuel in the following ratio: half is produced in seasonal storage by a wood chipper driven by a tractor using the low-quality wood purchased by FDJ, and half is purchased as wood chip fuel from suppliers. In this case, part of the fuel produced for the heating plant would be supplied by FDJ in the form of low-quality wood, approximately 3300 m^3 full cubic meters per year. This scenario is 50% dependent on the market prices of wood chips (C1 criteria).

The third scenario refers to a completely independent production process of wood chips by using a wood chipper driven by a tractor at seasonal storage. In that case, the supply of low-quality wood in the full amount (approximately 6600 m^3 full cubic meter per year) should be delivered by FDJ. This scenario is 0% dependent on the market prices of wood chips (C1 criteria).

In scenarios 2 and 3, the tractor has multipurpose roles and can be used for transporting wood chips in a trailer to the heating plant.

The formation of wood chip prices is best done according to the individual elements that participate in the supply chain, like per chipper, per transport, etc. One very interesting platform for the creation and logistics of bioenergy projects and their optimization is in the process of development and can be used for these purposes (https://dep.dignet.hr/) [15]. In Table 3, an approximate method for calculating the prices of wood chips for scenarios 2 and 3 is given. All values in the table refer to fresh wood chips (50% moisture) (mainly conifers).

Table 3. Test results of classification

Method of Implementation	**Scenario**			
	3		1	2
Price of low wood quality in BAM per m^3 (full cubic meter)	70 sources by (FDJ)	Conversion to BAM per ton 84	Current price of wood chips 140	50% of the third and 50% of the first scenario participate in price (own production and procurement from the wood chip market)
Transportation to seasonal storage in BAM per m^3 (full cubic meter)	20 sources by (FDJ)	Conversion to BAM per ton 24		
Wood chipper costs, BAM per ton	-	7		
Manipulation from the wood chip storage to the heating plant	-	5		
Overall price per ton of wood chips (BAM per ton)	-	120	140	130

The Multi-Criteria Decision-Making (MCDM) analysis (entropy method for determining criteria weights for C1, C2, and C3) and the VIKOR method for selecting the optimal option were applied to the three scenarios given in Table 2 and Table 3. According to these methods, scenarios 3 and 2 were selected as optimal in wood chip fuel supply logistics. In addition, scenario 2 was confirmed as optimal with the Preference Selection Index (PSI) method [22].

6 Results and Discussion

Zero projected heat prices (without making a profit) related to the wood chip prices and gross price of human labor would not deviate much, ranging from 10.5 to 11.5 pfennigs per kWh produced or 105 to 115 BAM per MWh produced. In this calculation, the following data were taken into account: the gross average annual human labor price of 530 000 BAM in the heating plant [9], the cost of wood chip fuel per year (695147 to 811005 BAM), the number of employees (25) [9], the price of wood chips used in the interval from 120 to 140 BAM per ton, and the heat generation per year of 11660 MWh. In some options, it can be considered that the local forest company can supply low-quality wood to the heating plant at subsidized prices, and in this case, the price of wood chips could be set at 80 BAM per ton.

Regarding the new plant itself, there are some requirements and limitations regarding its realization. One of the first demands of the municipality is that the seasonal storage of wood chips be relocated from the location of the new heating plant due to noise, damage to the visual space, and the unnecessary occupation of a larger land area close to the city. The fact is that it causes an additional cost, but it must be taken into account. Another important thing is the seasonal storage of wood chips and the capacities, which must be taken into account due to the difficult winter conditions in this area. This certainly increases the level of investment. Any plant with a heat capacity of 10 MW must have its own independent system for producing wood chips because local suppliers would create market disturbances in the supply on the one hand. On the other hand, competition with pellet producers would be reduced, and this would relax the biomass market significantly. Stored amounts of naturally dried wood chips (30% moisture) in seasonal storage during the summertime would be enough to cover almost 2.5 months of fuel needs, which is a very good thing for safety in the winter period. The additional effect is that human resources in the heating plant are engaged in producing wood chips as fuel because of the organization of work, which represents a very sustainable business integrated at the heating plant with a high degree of independence.

Basically, a systematic approach was presented in this study for analyzing the district heating systems supplied with wood chips as a renewable biomass fuel. Figure 2 shows a scheme for planning and using wood chips as fuel in the district heating systems.

In the process of analyzing the profitability of the district heating system, besides considering the logistics and security of wood chip supply as fuel, some simple payback scenarios for the project were also analyzed. In this regard, proprietary calculation models were used for both the plant and the logistics process. Additionally, the plant and logistics model was created on DEP [15]. DEP is a tool enabling the simplification of complex, biomass-based energy production-related calculations, while also enabling the customization of each individual element in the bioenergy production process. The user can use a simple procedure to "simulate" the production parameters and choose the best option from a set of biomass-based projects. Figure 3 shows the appearance of DEP and its application in defining a real project for the district heating system in Pale with the logistics supply chain of wood chips.

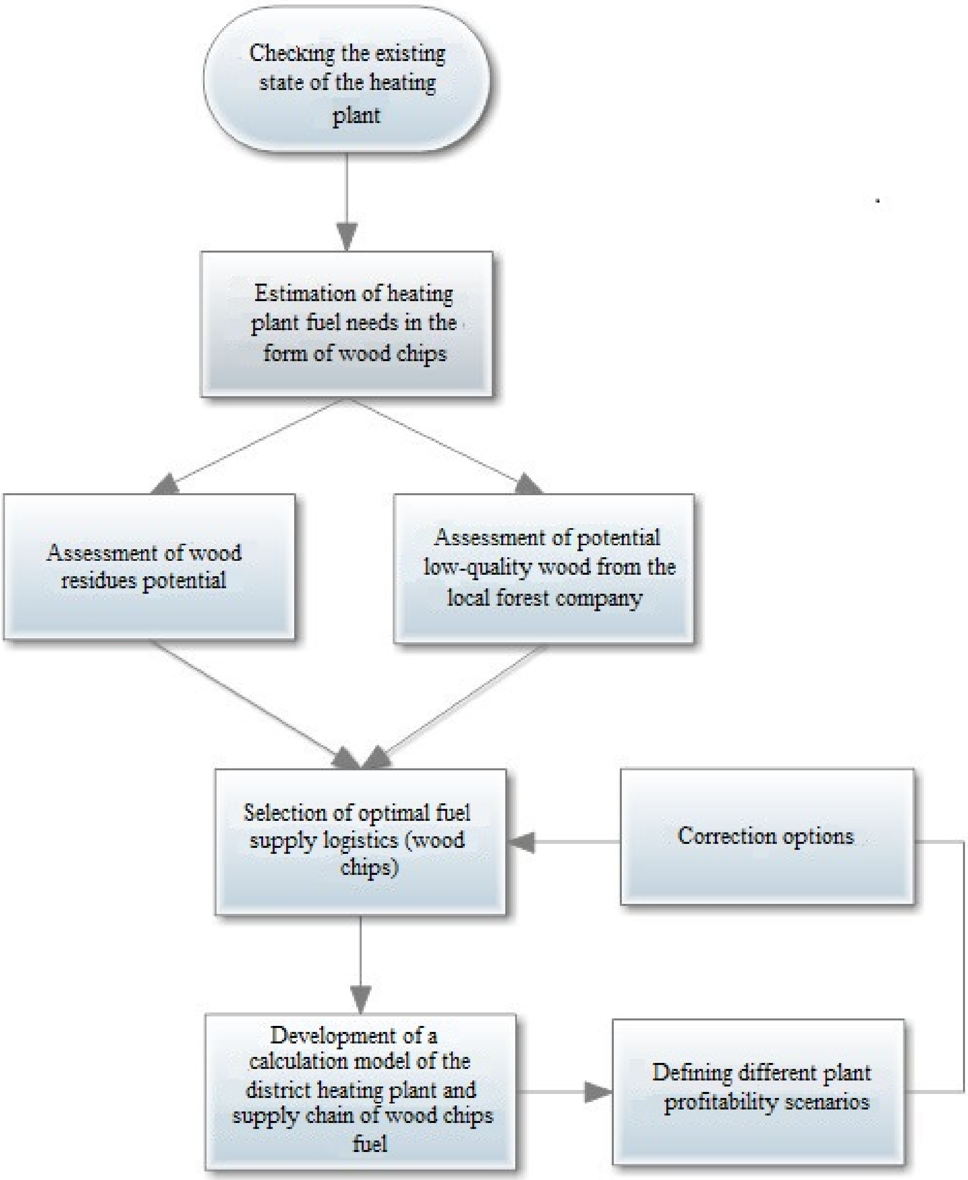

Figure 2. Protocol scheme for planning and using wood chips as fuel in the district heating plants

Various scenarios showed that the payback period for the investment in the district heating system project in the municipality of Pale is quite long, ranging between 19 and 30 years. This information refers solely to the case of heat energy distribution and sale at the proposed price of approximately 165 BAM/MWh. The project in question would include the renovation and installation of a new distribution network, the replacement of the old boiler with a new 10 MW wood chip boiler, the installation of a 10 MW backup gas boiler, the purchase of machinery for wood chip production and transport, and the construction of a storage facility for wood chips. The total investment in this project would amount to around 20 million BAM [23].

The lowest wood chip price used in the payback period scenario was approximately 80 BAM/ton, while the highest was about 140 EUR/ton. Given that the wood chip production machine would not be used at full capacity solely for supplying the heating plant in Pale, it would be possible to develop additional business activities involving the processing, production, and sale of wood chips. The annual processing capacity of the machine could reach up to around 24,000 tons, which would represent about 50% utilization of the wood chip production machine, based on its productivity of 140 m^3/h. In that case, the profitability of the project would increase significantly, and the revenue from wood chip processing and sales could be roughly equivalent to that from heat energy sales. The payback period would then fall within the range of 10 to 15 years, representing major progress, sustainability, and a strong advantage for this project. The considered quantity of 24,000 tons aligns with the assessed biomass availability in this locality.

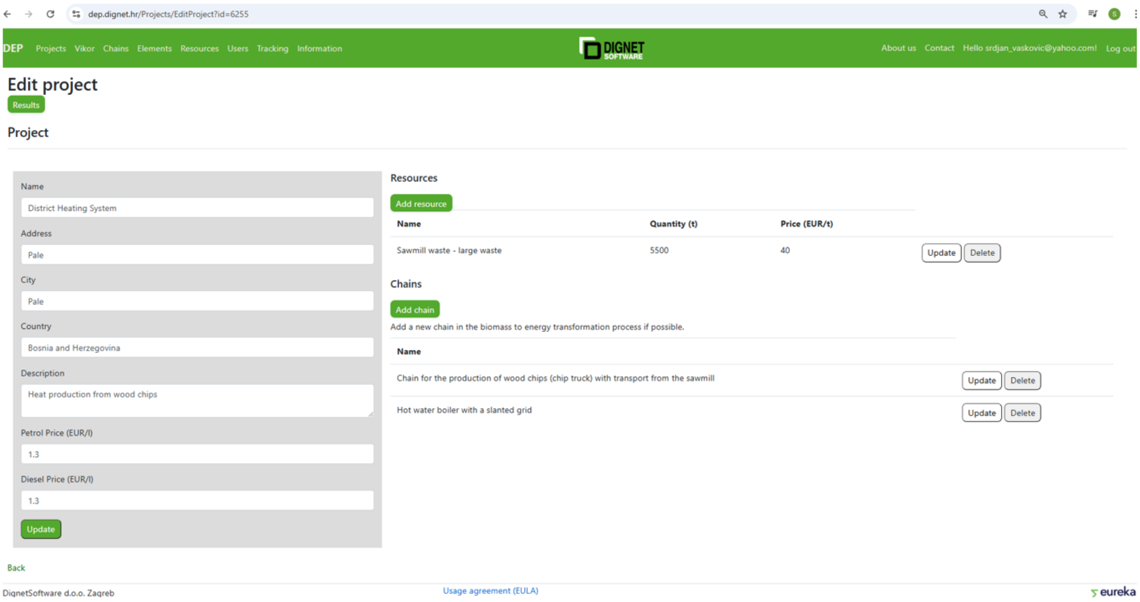

Figure 3. DEP in practical use for defining the district heating system project in Pale and the logistics supply chain for wood chips [15]

7 Conclusions

It has to be emphasized that, despite the relatively long investment payback period for the district heating systems, such projects are of great importance for the development of local communities—such as the municipality of Pale in the case study—for several reasons as follows:

-By choosing wood chips as a locally available fuel, energy security in heat supply is achieved.

-The construction of a new heating plant brings significant savings compared to the old facility, which operates with very low efficiency.

-The plant's capacity is expanded for the same fuel consumption, along with the heat distribution zones and the thermal energy distribution network.

-Both direct and indirect ecological savings are achieved.

-A significant improvement in thermal comfort for end users is ensured.

-The electricity distribution network is indirectly relieved to a considerable extent, among other benefits.

Although investment payback periods for the district heating system and the heating plant project are typically slow, such projects should be prioritized due to the numerous aforementioned advantages. By combining district heating systems with small-scale cogeneration and additional business activities, efforts can be made to establish viable and sustainable business and economic models. In this study, one such additional business opportunity for the heating plant was identified in the processing, production, and distribution of wood chips. Furthermore, public-private partnerships and cooperation agreements between heating plants and local forestry companies represent a key prerequisite for the project's success and the development of the local community.

This study presents a comprehensive and systematic approach to analyzing district heating systems and proposes a general protocol for planning and using wood chips in such systems. Of particular importance is the use of the MCDM optimization as an essential decision-making process, especially for projects that rely on renewable energy sources such as biomass.

Future research related to the construction or renovation of district heating systems should focus on the development of different models that can significantly contribute to the energy efficiency and profitability of such projects. In addition, similar analyses should also be carried out for the development of district cooling systems in other localities where such needs exist.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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