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The effectiveness of heating of housing unit by renewable energy source

J. Jobbágy, K. Krištof, M. Andacký

Department of Machines and Production Biosystems, Faculty of Engineering,
Slovak University of Agriculture in Nitra, Nitra, Slovak Republic

Abstract

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The paper is aimed at pointing out possibilities of using of dendromass for heating. The object of interest was heating of housing units with 75.27 m^2 of total area. The average value of dendromass moisture was 17.71%. The inserted fireplace Nordica Focolare 70 with a nominal output of 9 kW was used as a heat source. For temperature measurement, a non-contact infrared thermometer GM 900 was used. The total heat loss transferred through walls of housing unit (heat loss through thermal bridges and ventilation losses) were calculated at the value of 176.26 W/K. Based on the results of samples moisture the net calorific value of one kilogram of burned fuel wood was determined (14.791 MJ kg). The amount of thermal energy which is necessary to supply by the heating system for the whole heating period was 14,199.18 kWh. The weight of raw fuel wood was 5,450.97 kg (at moisture of 30%), dried at 17.71% (4,636.87 kg). Price of raw fuel wood of acacia for the year under evaluation was 64.80 €/m^3 (the required amount of raw fuel wood for heating period was 10 m^3). Total costs for the heating season was thus 648 €. The price of heat transmitted by the fireplace inset Nordica Focolare 70 inserted into heating system using fuel wood (white acacia) with 17.71% of absolute moisture was 0.045636 €/kWh.

Keywords: heating costs; heat loss; fuel wood; fuel wood moisture

Dendromass is now a popular form of biomass, which is useful for the production of heat and electricity (Manzano-Agugliaro et al. 2013). The available annual share of energy from woody biomass accounts for about 47 PJ (Piszczalka, Jobbágy 2012). Dendromass is a product consisting of lignified plant matter or of lignified plant matter from agriculture (Ampatzi et al. 2013), wood-processing industry or from other sources such as e.g. communal sphere that can be used to produce energy (Trenčiansky 2007; Sharma et al. 2015). In the last 30 years, in order to increase production of woody biomass for energy purposes plantations of woody biomass were established of fast-growing trees with a minimum production volume 10 m^3/ha/year (Dzurenda et al. 2010; Sovacool 2012). More widely it is also grown in plantations for energy acquirement of dendromass (Rowell, Carpenter 1983; Harrison et al. 1986; Stringer, Carpenter 1986; Bringen 1992; Freitas et al. 2015). The aim of the study was to evaluate the utilisation of dendromass for heating of selected buildings.

MATERIAL AND METHODS

Thermal energy requirements for heating of housing unit. The housing unit had the concept of a three-room apartment with the total area of

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75.27 m^2 (Fig. 1). Substantial heat loss constitutes losses through the peripheral walls. In the study, other heat losses were also taken into account, e.g. through windows and doors. Heat losses transferred through the floor are lower due to its total basement. Above the studied housing unit there is another housing unit with approximately equal room temperature and therefore heat loss through the ceiling were not taken into account. Transmittance of the building envelope was determined. The primary use of the measurements were to determine the thermal performance of the selected building. In addition, passive solar heat gain and interior heat gain were considered. Passive solar gains are dependent on sunlight, which is different for each month and therefore the values of thermal energy of passive solar gains were determined for each month individually. Interior heat gain is made up by the human activity (metabolic heat) and electrical appliances in the housing unit. These, seemingly, low heat gains constitute a considerable component and their consideration will contribute to clarification of our values to determine the resulting thermal energy needs for heating. When evaluating the heat source and heating system, the average length of the heating season of 206 days was considered depending on the climatic region.

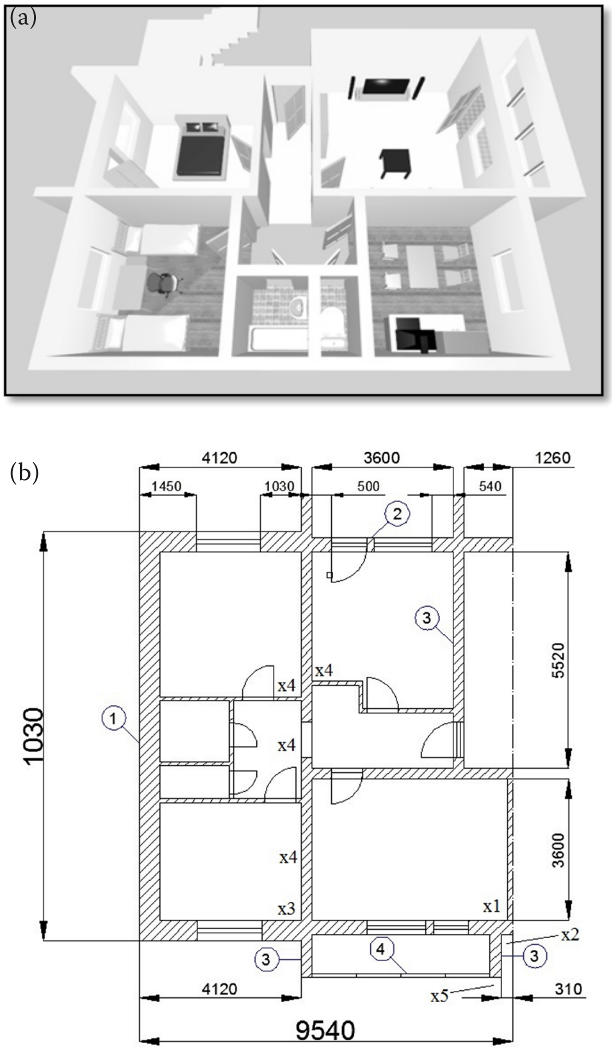

Fig. 1. Disposition of the housing unit (a) 3D vizualization and (b) ground plan

1 – fireplace; 2 – flue pipe; 3 – blower; 4 – exit of heated air; 5 – external air supply

Climatic conditions in Nitra are determined by the location in the northern temperate zone with altitude up to 400 m a.s.l. with an average temperature 3.8°C during the heating season. Thermal resistance and thermal transmittance were determined according to Chmúrny (2003).

The total heat loss through the construction of housing unit. Total heat losses were determined according to Chmúrny (2003) and Ampatzi et al. (2013) by the following equation:

$$H_T = H_P + H_{TM} + H_V \qquad \text{(W/K)} \qquad (3)$$

where: H_T – total heat loss through the housing unit construction by transition (W/K); H_P – heat loss transferred through the housing unit construction (W/K); H_{TM} – heat loss transferred through the thermal bridges (W/K); H_V – heat loss due to ventilation (W/K)

Properties of burned fuel wood (dendromass). Dendromass input (white acacia) represents 1.73% of the whole dendromass in the forests of Slovakia (for year 2010), which represents an area of 33,308.91 hectares. Important feature of dendromass is its moisture (Lattimore et al. 2013). When fuel wood is properly dried, its net calorific value is increased (Singh et al. 2014). This finding is important because moisture in the fuel wood is released also in the fireplace at the expense of combustion heat. When burning fuel wood with higher moisture, combustion temperature decreases, which leads to a false oxidation of all combustible components and leads to creation of carbon blacks and clogging of the chimney (Gasol et al. 2010; Nasser, Aref 2014). For moisture (absolute) measurements of combusted fuel wood a tipped resistance moisture meter was used (Fig. 2; ETI 8040, Moisture tester; ETI, West Sussex, United Kingdom). Net calorific value of the burned fuel wood was determined according to Pastorek et al. (2004):

Fig. 2. Moisture meter ETI (a), Nordica Focolare 70 (b) and thermometer GM 900 (c)

$$H_p = \frac{H_s \times (100 - w_p) - (r \times w_p)}{100} \qquad (4)$$

where: H_p – net calorific value of burned fuel wood (MJ/kg); H_s – net calorific value of dry matter (MJ/kg), w_p – mean value of burned fuel wood moisture (%); r – heat needed for evaporation of 1 kg of moisture (2.44 MJ)

Characteristics of the heat source: the fireplace insert Nordica Focolare 70 was used as a heat source (Fig. 2; single-cylinder gray cast iron; La Nordica SpA, Vicenza, Italy) with a nominal 9 kW power output. Fireplace insert with a weight of 145 kg achieves efficiency of 79.7% and average hourly fuel wood consumption of 2.6 kg/h. Power output of the selected fireplace is adjustable from 5 to 13 kW.

For temperature measurement a non-contact infrared thermometer GM900 was used (Jumaoyuan Shenzhen Science & Technology Co., Ltd., Shenzhen, Guangdong, China). The laser beam allows the precise focus of the object. Thermometer consists of optics, temperature sensor and LCD display.

The effectiveness of the heat source:

$$\mu_{NFi} = \frac{Q_{di}}{H_p \times m_{pi}} \qquad (1)$$

where: μ_{NFi} – efficiency heating system with a heat source Nordica during the i-th measurement; Q_{di} – the amount of heat required to cover the heat loss during the i-th measured day (kWh); H_p – net calorific value of the burned fuel wood (kWh/kg); m_{pi} – the mass of burned fuel during the i-th measurement (kg)

Heating costs in relation with other alternatives. A specified final value of the costs for burned fuel wood in the fireplace insert Nordica Focolare 70 were determined and the results were compared with other alternatives of fuel wood burning (with the same input value of the housing units). For an objective assessment of the thermal potential of fuel wood, other methods of heating were compared, which are also commonly used as a source of heat in the area of our study.

Price of thermal energy:

$$C_{TZ} = \frac{C_{EN}}{\mu_{TZ}} \qquad (€/kWh) \qquad (2)$$

where: C_{TZ} – the price of thermal energy transferred into the heating system by heat sources (€/kWh); C_{EN} – price of energy consumed (€/kWh); μ_{TZ} – efficiency of heat source

RESULTS AND DISCUSSION

The required thermal energy for heating of housing unit

Energy consumed for heating dwelling unit is the result of the interaction of thermal properties of building constructions, buildings and heating system as well as the present condition of the internal and external environment (Fernandes et al. 2011; Ampatzi et al. 2013). Construction of housing units is mostly made of standard bricks, concrete, isolation and plaster. However, in terms of layout and layer thicknesses of construction materials there were divided five types of walls (Sharma et al. 2015). The arrangement of these types of walls in building structures is shown in Fig. 1b. Parameters λ (thermal conductivity) and d (thickness of construction materials) are input for the thermal resistance and thermal transmittance calculations, where thermal resistance is the ability of a mate-

Table 1. Thermal resistance and thermal losses

	Material	Area (m^2)	Total thermal resistance ($m^2/K/W$)	Heat transfer coefficient ($W/K/m^2$)	Heat loss (W/K)
Wall No. 1	brick PDT, concrete, polystyrene, plaster	37.27	2.209	0.4527	16.87
Wall No. 2	brick PDT, polystyrene, plaster	5.16	1.902	0.5258	2.71
Wall No. 3	brick, plaster	17.89	0.346	2.8902	33.95
Wall No. 4	aerated concrete polystyrene, plaster	4.55	0.878	1.1386	5.18
Floors	PVC, concrete, polystyrene	75.27	1.283	0.7794	31.28
Windows	glass, plastic	15.37	–	1.44	22.13
Doors	–	1.8	–	4	7.2
Ceiling	–	75.27	–	–	–
Sum	–	232.58	–	–	119.32

rial to retain heat (Freitas et al. 2015). With an increase of thermal resistance of the structure, it has a better thermal insulation capability. Heat transfer coefficient is actually the inverse of the thermal resistance (Table 1). Therefore, the higher its value, the better thermal insulation properties material or structure has (Sharma et al. 2015; Manzone et al. 2015). External cladding of housing units is also formed by windows and doors. In this case, however, the values of heat transfer coefficient were not calculated because it was already specified by its manufacturers.

The total heat loss through the construction of housing unit

After the values of heat transfer coefficients were calculated for elements of building wall construction, the particular energy values of heat losses were calculated. The issue of heat loss consists of three basic components of heat loss and they are the direct transfer of heat through construction (H_P), through thermal bridges (H_{TM}) and heat loss due to ventilation (H_V) defined by Ampatzi et al. (2013).

When calculating heat losses H_P (direct heat loss transferred through the housing unit construction) the value of heat transfer coefficient must be taken into account for shell elements and the corresponding reduction factor (reduction factor for external walls, windows = 1, unheated part of the walls = 0.5).

To determine the heat loss transferred through the thermal bridges – H_{TM}, it was necessary to determine an approximate average value of heat losses per 1 m^2 for all the structural elements of the housing unit walls (0.1 $W/m^2/K$). Total heat losses through thermal bridges of 23.26 W/K were calculated.

Heat loss due to ventilation (H_V) depends on tightness of living space, i.e. on factor how quickly the indoor air can be replaced by outdoor air. As the sample, the conditions were considered that the total volume of air exchange in living space takes 0.5 hours. Total losses, H_V, were calculated as 33.67 W/K.

The value H_T = 176.25 W/K represents total heat losses of housing unit in relation with difference between inside and outside temperature and determines the requirements of heating system performance. Nominal heat output of fireplace insert at 9 kW can thus cover the heat losses of housing units up to –30°C of outside temperature when considering an internal temperature of 23°C. That demonstrates the oversizing of the heat source, which therefore it is not used in its best combustion efficiency in this case.

Passive solar gains through the glass surfaces

Even during the heating season and winter months, the interior receives heat in the form of sunlight. This sunlight is not as intense as in the summer months, but nonetheless, it constitutes a non-negligible energetic value as a passive heat gain. Based on the orientation of the housing unit, according to cardinal points, the size of glass surfaces and other constants (such as type of glass, glass purity, etc.) influencing heat received to the interior were determined. The heat gained through passive solar gains through glass areas for one heating period was 804.83 kWh.

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Heat gains from the other internal sources

Internal heat gains include all produced heat in the interior in addition to the heat from the heating system and solar heat gains. In particular, it is about heat produced by human activity (metabolic heat), installed appliances and lighting and heat extracted from the distribution of hot water and sewage systems (Freitas et al. 2015). Heat from internal resources was calculated as 1860.72 kWh (while average thermal performance of internal heat source for housing unit was considered as 5 W/m^2).

Calculation of the thermal energy requirements for heating

In calculating the quantity of thermal energy for heating in the heating period, the average temperature throughout the heating season has to be mentioned. Mean temperature value is based on the course of the outside air temperatures. From this value, it was possible to determine the theoretical amount of thermal energy needed for the whole heating season.

The amount of heat energy required to cover the total heat loss of housing units (Q_t) for one heating period was 16731.45 kWh (degree days D = 3,955.2 K/day, the calculation is based on the difference between the mean interior temperature T_2 = 23°C and the mean exterior temperature T_1 = 3.8°C and the length of heating period d = 206 days) following Eq. (5).

From the energy balance of heat energy consumption on the one hand and passive solar gains and other heat gains on the other hand, heat was determined, which has to be conveyed by heating system for heating season (Q_h = 14,199.18 kWh).

The calculation of degree days:

$$D = (T_2 - T_1) \times d \qquad \text{(K/day)} \qquad (5)$$

The amount of the thermal energy required to cover the whole losses of housing unit (Q_t) were calculated as follows:

$$Q_{tVO} = \frac{D \times 24 \times H_T}{1{,}000} \qquad \text{kWh} \qquad (6)$$

where: Q_{tVO} – amount of thermal energy required to cover the whole thermal losses of housing unit for one heating period (kWh); D – day degrees (K/day); H_T – total thermal losses of heat transfer through the walls of the housing unit (W/K)

The energy balance and following calculation of required heat Q_h, which needs to be delivered by the heating system, were calculated as follows (considering μ = 0.95):

$$Q_h = Q_t - \mu(Q_i - Q_s) \qquad \text{(kWh)} \qquad (7)$$

where: Q_h – the heat that needs to be delivered by the heating system during one heating period (kWh); Q_t – amount of heat required to cover the whole heat losses of housing unit during one heating period (kWh); μ –factor of heat gains utilisation; Q_i – the heat generated by internal sources except of the heating system during one heating period (kWh); Q_s – heat obtained into interior from passive solar gains through glass areas during one heating period (kWh)

Properties of burned fuel wood

Moisture. Firewood (white acacia) is characterized by low absolute humidity immediately after extraction, and therefore requires a shorter time for drying (Table 2). The fuel wood used in the study was dried naturally for one year (to achieve absolute moisture 10–12% – even that one year is usually considered as short time) (Cutz et al. 2016). For this reason, the total fuel wood moisture of average value of 17.71% was observed.

Net calorific value. Fuel wood contains free and bound moisture in its structure (Sharma et al. 2015). During the combustion of fuel wood it increases the heating value of the heat required for evaporation of the moisture contained in it. Therefore, when calculating the net calorific value of fuel wood it is needed to know net calorific value of dry matter, which means the fuel wood combustive efficiency of fuel wood at 0% of absolute moisture (Ampatzi et al. 2013). Since this value is not commonly recognised in practise it is recommended to use calculation of the theoretical value, following Pastorek et al. (2004), H_s = 18.5 MJ/kg.

During the measurements of combustion characteristics of fuel wood, the focus was paid mainly to the measurement of absolute moisture and the subsequent calculation of the net calorific value of fuel wood. Moisture measurement by tipped moisture meter revealed the mean absolute moisture of burned fuel wood at 17.71%, which is a satisfactory value from energetic perspective.

Therefore, net calorific value of 1 kg of burned fuel wood was 14.791 MJ/kg meaning, 4.109 kWh/kg.

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Table 2. Descriptive statistics – fuel moisture

Parameter	Moisture of combusted fuel inside of the sample (%)	Moisture of combusted fuel at the sample (%)
Mean value	22.27	13.16
Standard deviation	3.91	1.25
Max-min difference	13.80	5.80
Maximum	28.10	16.50
Minimum	14.30	10.70
Quantity	20.00	20.00
Variance	15.32	1.56
Coefficient of variation	68.81	11.85

Characteristics of the heat source

Heating and cooling down of the heat source. In order to determine the reaction times of the fireplace insert Nordica Focolare 70, measurements of the heat-up time of the heat source were realized (Fig. 3a).

When cooling rates of the heat source are a specified time interval during which the case of the fireplace insert transmits heat even after burning out of all fuel wood in the combustion chamber (Fig. 3b). After burning out of all fuel wood the measurements of fireplace insert temperature began in a 15 min intervals for determining the continuous decrease of its temperature.

In contrast to linear chart progress for heat up of construction, the chart progress in case of cooling down the case better fit to the exponential curve. Due to the accumulation potential of grey cast iron, from which a fireplace insert is made of, it releases its heat through the shell for about 5 h after finishing of combustion in the combustion chamber.

The need of thermal power and heat. To determine the necessary thermal power and the necessary heat, it was proceeded by comparing the measured external and internal temperatures. Subsequently, on the basis of findings and already known value of the total heat loss (176.25 W/K) the heat output values were determined. Values were calculated and the interior and solar gains were included. Interior heat gains (5 W/m^2) in a housing unit total area of 75.27 m^2 constitute an approximate hourly 0.376 kWh of heat. Measurements were conducted in December (where: global solar radiation = 0.65 kWh/m^2). Theoretical value of solar heat gains 2.48 kWh were divided into ten hours during sunshine.

Afterwards, as interior and solar heat gain were subtracted from the necessary heating capacity to maintain the temperature in a given period of time, it leads to the amount of heat value, that it was necessary to be transferred by the heating system to housing unit.

From the measurement results of heat output and necessary heat, which needs to be delivered by heating system to housing unit during the day, the average efficiency for complete heating system can be determined. It means that it reflects an average efficiency during measured time scale where all combustion stages of fireplace insert are included. Nordica Focolare 70 producer stated its efficiency at 79.7%. The average efficiency of the heating system with a heat source Nordica Focolare 70 during the measured distance is expressed by the equation (1) referred to in methodology. The average efficiency of the heating system with a heat source Nordica Focolare 70 during the first measurement was 74.95% and in the second measurement 74.10% (Table 3).

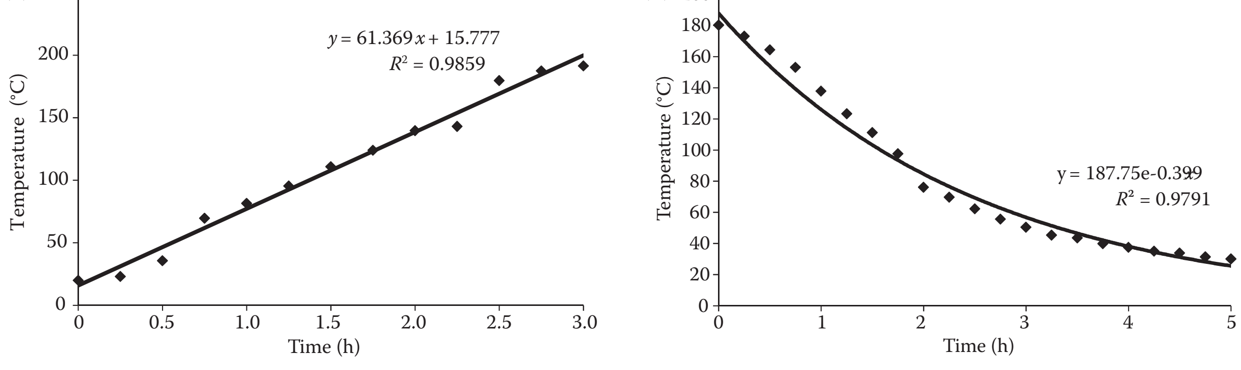

Fig. 3. Heating (a) and cooling (b) of the heat source progress

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From the measured and calculated values of temperatures during measurement it may be concluded that the need of heating power for the measurement period (24 hours) is not constant. Depending on the increase of the difference between the inside and outside temperatures, the need of thermal performance to maintain the daily interior temperature increases. This course of necessary thermal performance in time from 12:00 to 12:00 of the next day is shown in Fig. 4.

Heating costs

The calculation of the fuel wood consumption. The amount of thermal energy to be delivered by the heating system to housing unit for heating season, was 14,199.18 kWh. It is assumed that for the whole heating season white acacia will be used as fuel, with absolute moisture 17.71% and calorific value 4.109 kWh/kg. The required weight of fuel for heating period was 4,636.87 kg. Fuel wood, however, is largely sold in units of volume, not weight. Fuel wood volume immediately after extraction is changing over time, specific gravity of drying fuel wood decreases, respectively (Sharma et al. 2015). The average weight of white acacia in the extraction is 780 kg/m^3 and absolute moisture 30%. It means that 1 m^3 of this fuel wood contains 546 kg of dry matter and 234 kg of free and bonded moisture. By calculation, it was determined, that in absolute moisture 17.71%, the weight of fuel wood decreased by 117.51 kg (weight of the burned fuel wood 663.51 kg/m^3).

The total mass of the burned fuel wood was 4,636.87 kg at absolute moisture 17.71% contains in this condition 3,815.68 kg of dry matter and 821.19 kg of moisture. A difference in the ratio of those two components at the present stage (17.71% of moisture) and in the condition immediately after extraction (30% of moisture) is in the moisture content. Weight of fuel wood in the raw state was therefore 5,450.97 kg.

Weight of raw fuel wood of white acacia 780 kg/m^3 was determined (Lieskovský et al. 2014). From the determination of the weight of fuel wood for heating period (5,450.97 kg) the volume of raw fuel wood needed after extraction was determined as 6.99 m^3 (30% of moisture).

Fig. 5 shows the results of acquired volume of the burned fuel wood. It shows the amount of raw fuel wood with absolute moisture 30% which needs to be acquired if it will be combusted in absolute moisture ranging from 5 to 30%. It also shows that with a decrease of absolute moisture in which the fuel wood is combusted, the weight of needed fuel wood, decreased subsequently.

Calculation of the costs. The heating costs for one heating period only include the cost of fuel wood. The price of raw fuel wood of white acacia was determined as 64.80 €/m^3 for the year of calculation.

Based on the results the required amount of raw fuel wood for heating season was determined as 6.99 m^3. This value, however, defines the required volume in the unit of solid cubic meters (scm). According to Pastorek et al. (2004), to convert the

Table 3. The values for calculation of the average efficiency of the heating system

Parameter	Measurements	
	I	II
Average outside temperature/24 h	0.0°C	1.8°C
Average inside temperature/24 h	23.0°C	23.4°C
Average difference of inside and outside temperatures	23.0°C	21.6°C
Daily requirement of heating power	85.765 kWh	80.072 kWh
Burned fuel	white acacia	white acacia
Weight of the burned fuel	27.85 kg	26.30 kg
Calorific value of the burned fuel*	14.791 MJ/kg 4.109 kWh/kg	14.791 MJ/kg 4.109 kWh/kg
Energy value of the burned fuel*	411.93 MJ 114.43 kWh	389.00 MJ 108.06 kWh
The average efficiency of the heating system	74.95%	74.10%

I – 1st measurements; II – 2nd measurements;*measured values used in calculations with following conversion (kWh/kg to MJ/kg, kWh to MJ)

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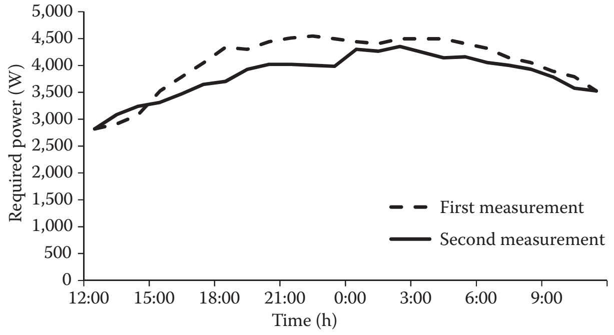

Fig. 4. The need for thermal performance for heating during the measurement period

units of solid cubic meters to cubic meter uses a coefficient with a numerical value 1.43. The costs of the burned fuel wood for one heating season were then determined as 648 €.

The average price of one kWh of thermal energy for heating by burning fuel wood of white acacia with absolute moisture 17.71% at fireplace insert Nordica Focolare 70 can be calculated as the share of the cost of the fuel wood burned for one heating season and the necessary amount of kWh required to keep the internal temperature at 23°C in housing units during the heating season. The price of one kWh of heat transmitted by the fireplace insert Nordica Focolare 70 into the heating system using fuel wood (white acacia) as fuel with absolute moisture 17.71% was 0.045636 €/kWh.

According to the recent research in the area, authors evaluated development as well as volume production of dendromass (Manzano-Agugliaro et al. 2013). From the results, the positive effect was observed and follows its use in the field of bio energy. An analysis of the assessment of research shows that intensive method of cultivation in subareas has a positive effect on height (12.9%) and diameter growth (14.0%), on volume production (30.6%) as well as the production of woody biomass of black locust in dry condition on 1 ha than when grown on the surface traditional method (Kohán 2010; Varnagiryte-Kabašinskiene 2012).

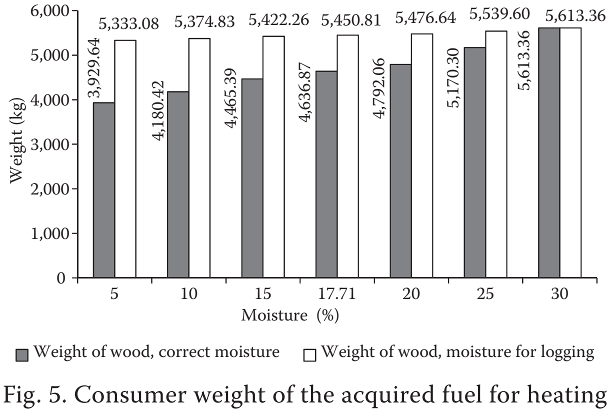

Fig. 5. Consumer weight of the acquired fuel for heating season of housing unit

White acacia wood with higher density, higher net calorific value and lower ash content compared to poplar and willow wood proved to be a more suitable raw material that may be used as a renewable energy source (Ampatzi et al. 2013), regarding the production of heat energy (by combustion) per biomass weight (kg). However, it is very important, from the aspect of the application of fuel wood of these tree species as renewable raw materials for energy, to also consider the influence of the biomass annual yield per unit area of the plantations established as "energy plantations" (Klašnja et al. 2013; Manzano-Agugliaro et al. 2013).

The fuel wood consumption and costs of two types of fuel (gas and wood) used for heating were tested in the buildings. At annual energy demand of 94,000 MJ, burning of fuel wood resulted in savings of about 35%, based on gas prices from 2003 and fuel wood prices from 2006 (Piszczalka et al. 2007).

Woodchip sampling may be done according to two methodologies, based on the volume or net calorific value of the fuel wood. The studies compared heating values obtained through relative moisture measurements according to the Slovak technical standards and through determination of net calorific value according to the ISO 1928:2003 standard. Based on the established facts it may be said that heating capacity values obtained using both studied methodologies differ significantly in the sample set (Kumar et al. 1999; Manzano-Agugliaro et al. 2013; Lieskovský et al. 2014; Freitas et al. 2015).

CONCLUSION

In evaluating the use of dendromass for heating, it was concluded that the most significant advantages of this alternative heating system are its availability and low cost of used fuel wood. In the calculation of prices of heat by combustion of fuel wood, briquettes and pellets, the price of thermal energy transferred by burning of fuel wood always dominated. For the combustion of fuel wood (white acacia), the price of heating energy was 0.045636 €/kWh. When compared to other alternatives of heating as

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e.g. application of condensing boiler with efficiency 95%, per unit cost was increased to 0.0506 €/kWh (the price of natural gas for the examination term C_{zp} = 0.0481 €/kWh). If electric boiler would be applied in heating system (simple system in terms of handling and difficulty) it would be even higher, as 0.0594 €/kWh (boiler efficiency 99%, price of electricity from a supplier in a given year 0.0588 €/kWh).

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Corresponding author:

Ján Jobbágy, Slovak University of Agriculture in Nitra, Faculty of Engineering, Department of Machines and Production Biosystems, Tr. A. Hlinku 2, 949 76 Nitra, Slovak Republic; e-mail: jan.jobbagy@uniag.sk