ACTA SCIENTIARUM POLONORUM
Acta Sci. Pol.
Silv. Colendar. Rat. Ind. Lignar. 11(3) 2012, 65-76

COMPARATIVE ANALYSIS OF THE CALORIFIC VALUE OF GIANT FIR TIMBER (*ABIES GRANDIS* LINDL.) FROM VARIOUS STANDS IN SOUTHERN POLAND

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Abstract. The paper presents a comparative analysis of wood calorific value of grand fir (*Abies grandis* Lindl.), originating from four stands of the southern Poland. The research material were the samples, collected from the trunks of 30 trees in each stand. The samples were divided into sections, each containing five annual increments. Then each section was measured: annual ring width and the relative wood density, which was converted to dry wood density, taking the total volumetric shrinkage of 11%. It was assumed that the calorific value of 1 kg dry wood of grand fir is 20.15 MJ. On the basis on the analysis it was found that the average calorific value of 1 m^3 of grand fir wood was 8021 MJ. It was shown, that a significantly higher calorific value was obtained by the combustion of 1 m^3 wood of giant fir trees, growing on the poorer soil in comparison to the more fertile soils. Statistical analysis also showed that with increasing age of the trees the calorific value of 1 m^3 grand fir wood increases significantly.

Key words: giant fir, timber, calorific value

INTRODUCTION AND AIM

According to the document "Polish Energy Policy until 2030" [Polityka... 2009], adopted in Act No. 202/2009 of 10 November 2009, the share of renewable energy sources in the Polish energy balance is expected to increase to the level of at least 15% by 2020. One of the most important renewable energy sources is biomass, especially timber. Taking into account the above-mentioned Act, the trend towards steady increase in timber consumption for heating purposes [Mały rocznik... 2010] is likely to remain in Poland for a long time. Therefore, in recent years, more attention has been paid to fast-growing species of trees that could be grown on energy plantations. In 2011, the area of such plantations in the world comprised 3.8% of the world's total forest area [Gil 2011]. The most common species grown for this purpose in Poland is basket willow (*Salix viminalis* L.), but more and more attention is being paid in Poland to foreign fast-

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growing tree species. North American giant fir (*Abies grandis* Lindl.) is one of them. In the United States, the timber of this species is commonly used as fuel [Hanley 1979]. Since 1970s, within a IUFRO experiment, research has been conducted on the provenance of giant fir in Poland [Kulej and Socha 2005, 2008], Germany [Konig 1995, Rau et al. 1998] and in 15 other European countries.

Outside that IUFRO experiment, also in the late 1970s, giant fir was planted in several stands in southern Poland. Currently, these trees are slightly above 30 years old. Since 2010, the Department of Forest and Wood Utilization at the University of Agriculture in Krakow, has been conducting research on giant fir timber from the above-mentioned stands.

The aim of the present paper is comparative analysis of the calorific value, understood here as the heat of combustion, of giant fir timber originating from selected stands in southern Poland.

METHODOLOGY

Field work was conducted in 2010, in four stands located in the following forest subdistricts: Tokarnia, Kornatka, Kamianna and Feleczyn. The first two subdistricts are a part of the Myślenice Forest District, while the other two belong to the Nawojowa Forest District; both forest districts are located within the territory of the Regional Directorate of State Forests in Krakow. The location, as well as the site and stand characteristics of the research plots are shown in Table 1.

In each stand, in a place representing the average conditions for the growth of trees, there was established a research plot of the size of 0.2 ha, there the breast-height diameters of all living fir trees were measured. The resulting values were assigned to the respective tree thickness classes. Then, in proportion to the number of trees in these classes, 30 sample trees were selected. From each of them one sample was collected with the use of an incremental borer. The sample was collected along the radius of the cross-section, at the height of 1.3 m above the ground, on the north side of the stem. These samples constituted the material for laboratory tests.

In each sample, the width of annual rings was measured using the "Przyrost WP" software [Przyrostomierz... 2001]. Then the relative density of wood was determined, representing the ratio of mass of absolutely dry timber and its volume in the state of maximum swelling. This characteristic was measured in sections of a sample comprising 5 annual increments starting from the girth. The last, core section included in general fewer than 5 increments.

Sections of the samples were dried in the oven with a thermostat in the temperature of 103 ±2°C until obtaining an absolutely dry state, then they were weighed on an electronic scale with an accuracy of 0.001 g. Section volume was determined according to the method described by Olesen [1971], which assumes a hydrostatic method of measuring the volume (water removal) in a state of maximum swelling of wood, which is obtained after the unattended sinking of samples (their sections), placed in test tubes with distilled water. Relative wood density, calculated for each section, was then converted to the absolute density, i.e. density of absolutely dry wood, assuming the total volume shrinkage of fir wood to be 11% [Krzysik 1974, The Wood... 2008].

Table 1. Location as well as the site and stand characteristics of the research plots
Tabela 1. Lokalizacja oraz charakterystyka siedliskowo-drzewostanowa powierzchni badawczych

Forest district, forest subdistrict, division, plot Nadleśnictwo, leśnictwo, oddział, powierzchnia	Age* Wiek*	Species composition Skład gatunkowy	Site type of forest Siedliskowy typ lasu	Type and subtype of soil Typ i podtyp gleby	Stand density index Zadrzewienie
Myślenice	23	3 Jd	LMG	brown acid brunatna kwaśna	0.8
Tokarnia, 241 f (-01)	23	Bk 1			
1.33 ha	23	1 Św			
	33	2 Jd ol			
	23	1 Md			
	43	1 JD			
Myślenice	43	6 Jd	LMwyż	rusty podzolic rdzawa bielicowa	0.7
Kornatka, 99 c	33	4 Jd ol			
4.16 ha					
Nawojowa	35	10 Jd ol	LG	brown acid brunatna kwaśna	2.2
Kamianna, 110 b					
1.49 ha					
Nawojowa	35	8 Jd ol	LG	brown acid brunatna kwaśna	1.8
Feleczyn, 349 c	60	1 Wz			
0.85 ha	11	1 Dg			

*In the year of research, i.e. 2010.
Jd – fir, Bk – beech, Św – spruce, Jd ol – giant fir, Md – larch, Wz – elm, Dg – Douglas fir, LMG – mixed mountain forest, LMwyż – upland mixed forest, LG – mounta inforest.
*W roku prowadzenia badań, tj. 2010.
Jd – jodła, Bk – buk, Św – świerk, Jd ol – jodła olbrzymia, Md – modrzew, Wz – wiąz, Dg – daglezja, LMG – las mieszany górski, LMwyż – las mieszany wyżynny, LG – las górski.

The resultant absolute wood density of individual sections of each sample was converted to the density for the breast-height cross-section, by calculating – according to the methodology adopted by Ericson [1959] – the weighted average of the shares of each section in the area of this cross-section. For this purpose, researchers calculated ring areas which included – in the stem cross-section – annual increments that belonged to each section. The surface of the last, core section of each sample was calculated as the area of a circle. The size of the diameter of this circle was the difference in the breast-height diameter of a tree without bark and the double sum of the width of annual rings that made up the remaining sections of the sample. The area of the breast-height cross-section of the stem without bark (P) was calculated using the following formula:

$$P = \frac{\Pi \cdot (D - 2 \cdot G_k)^2}{4}$$

where:

D – breast-height diameter of a tree,
G_k – bark thickness.

On the basis of the measurements of bark thickness in blocks obtained at both research plots from the butt-ends of six giant fir trees, the bark thickness assumed in the above calculations was 5 mm.

The absolute wood density at the breast-height cross-section of the stems of giant fir trees was determined for three periods: the current one, which took into account all annual increments in a sample, as well as the periods 5 and 10 years back, for which respectively the last 5 and 10 annual rings were disregarded. Knowing the density of wood for particular periods, and assuming the calorific value of absolutely dry wood of giant fir to be 20.149 $MJ \cdot kg^{-1}$ [Wilson et al. 1987], the amount of combustion heat was calculated which could be obtained by burning 1 m^3 of the timber of this species.

The data obtained for the periods under consideration were juxtaposed and the researchers calculated the mean values and coefficients of variability for the sample trees, the research plots and all the material analysed.

Because of the lack of accordance of the empirical distributions of the obtained data with the normal distribution, proved with the Shapiro-Wilk test, the significance of differences was tested using the Kruskal-Wallis test (KW test). To assess which of the compared variables are responsible for the rejection of the null hypothesis of a lack of significant differences, multiple comparisons test was used. In these analyses, the level of significance $p \leq 0.05$ [Stanisz 1998, Statistica... 2008] was assumed.

RESULTS

Overall, the analyses included the wood samples obtained by drilling 119 stems of giant fir trees growing in four research plots. The condition of one of the samples prevented the possibility to carry out the analyses.

The mean calorific value of 1 m^3 of the examined giant fir timber was 8021 MJ for the current period; the average values in particular areas ranged from 7662 to 8498 MJ (Table 2). The coefficient of variability of the trait between the studied research plots reached 4.41%, and within a plot its value ranged from 9.1% to 15.9%.

The performed statistical tests showed that at present (in the current period) the combustion of 1 m^3 of giant fir timber from Kornatka would produce a significantly greater amount of heat in comparison with the trees from Tokarnia and Feleczyn (Table 3). The mean values obtained for the timber from these plots would be lower, respectively by 613 and 836 MJ (Fig. 1).

Assuming that the examined trees had been harvested 5 years ago, the heat of combustion of 1 m^3 of timber would have been an average of 7878 MJ, i.e. by about 143 MJ less compared to the value obtained at present (Table 2). The average values on particular plots would also have been lower, ranging from 7,555 MJ to 8,347 MJ. The variability of this trait would have been higher on the examined plots (Table 2). The amount of heat derived from the combustion of 1 m^3 of giant fir timber obtained 5 years ago from the plot in Kornatka would have been significantly higher as compared to trees from Tokarnia and Feleczyn (Table 4); differences in the mean values would have been respectively 608 and 792 MJ (Fig. 2).

Table 2. Combustion heat of 1 m^3 of giant fir timber
Tabela 2. Ciepło spalania 1 m^3 drewna jodły olbrzymiej

Name of research plot Nazwa powierzchni badawczej	Type of statistics Rodzaj statystyki	Period – Okres Current Bieżący	 5 years back 5 lat wstecz $MJ \cdot m^{-3x}$	 10 years back 10 lat wstecz
Tokarnia	$X_{śr}$	**7 884**	**7 739**	**7 740**
	V	9.8	10.3	12.2
Kornatka	$X_{śr}$	**8 498**	**8 347**	**7 964**
	V	10.4	12.5	13.8
Kamianna	$X_{śr}$	**8 041**	**7 872**	**7 751**
	V	15.9	17.0	14.7
Feleczyn	$X_{śr}$	**7 662**	**7 555**	**7 441**
	V	9.1	9.3	10.7
Total Ogółem	$X_{śr}$	**8 021**	**7 878**	**7 724**
	V	4.41	4.29	2.78

$X_{śr}$ – mean, V – coefficient of variability.
$X_{śr}$ – średnia, V – współczynnik zmienności.

Table 3. "p" values of the multiple comparison test for the current period
Tabela 3. Wartości „p" testu wielokrotnych porównań dla okresu bieżącego

Research plot Powierzchnia	Tokarnia	Kornatka	Kamianna
Kornatka	**0.02569**		
Kamianna	1.00000	0.63010	
Feleczyn	1.00000	**0.00071**	0.14700

K-W test: p = 0.0009.

Table 4. "p" values of the multiple comparison test for the period 5 years back
Tabela 4. Wartości „p" testu wielokrotnych porównań dla okresu 5 lat wstecz

Research plot Powierzchnia	Tokarnia	Kornatka	Kamianna
Kornatka	**0.01736**		
Kamianna	1.00000	0.60229	
Feleczyn	1.00000	**0.00142**	0.24170

KW test: p = 0.0013.

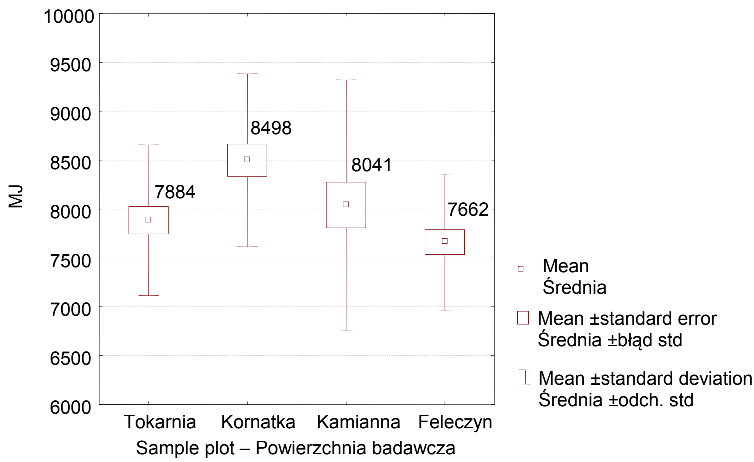

Fig. 1. Average calorific values of 1 m^3 of fir timber for the current period
Rys. 1. Średnie wartości ciepła spalania 1 m^3 drewna jodły olbrzymiej w okresie bieżącym

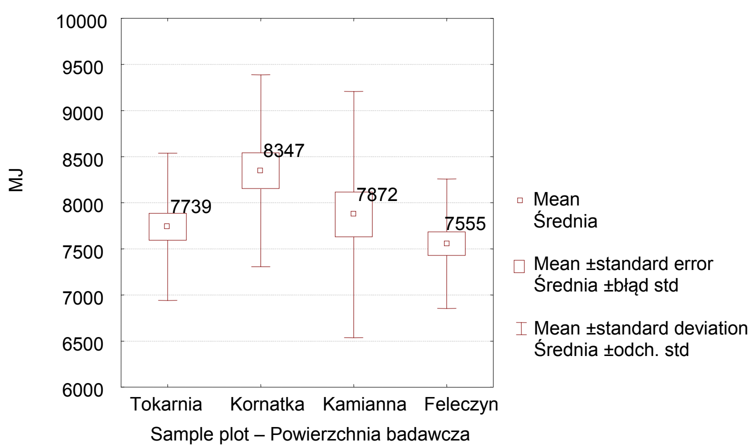

Fig. 2. Average calorific values of 1 m^3 of giant fir timber for the period 5 years back
Rys. 2. Średnie wartości ciepła spalania 1 m^3 drewna jodły olbrzymiej w okresie 5 lat wstecz

If the examined giant fir trees had been obtained 10 years before, the average amount of heat of combustion of 1 m^3 of timber would have been 7724 MJ; it would therefore have been by about 297 MJ lower compared to the value that could be obtained at present (Table 2). On plots in Kornatka, Kamianna and Feleczyn the mean values obtained for 1 m^3 would have been lower as compared to the later periods, while on the plot in Tokarnia about 1MJ higher calorific value would have been obtained as compared to the period 5 years back. On most plots, the coefficients of variability of this trait would have been highest during the period in question. Only in Kamianna the differentiation of this trait would have been lower as compared to the later period (i.e. 5 years back).

Statistical analyses showed that 10 years ago, the amount of heat obtained from combustion of 1 m^3 of giant fir timber from Kornatka would have been significantly higher as compared to trees from Feleczyn (Table 5). The mean values would have differed by 523 MJ (Fig. 3). Statistical analysis conducted for the whole material showed that, as compared to the period 10 years ago, now a significantly higher amount of heat would be obtained from the combustion of 1 m^3 of the examined giant fir timber (Table 6), and the mean values would differ by 297 MJ.

According to various authors cited by Krzysik [1974], calorific value of 1 kg of absolutely dry wood ranges from 17.7 MJ for goat willow to 22.6 MJ for pine. The units generally used in timber trade are units of volume, i.e. cubic meters (m^3) or steres. Thus, both for sellers of timber for energy purposes and for buyers, what is important is the amount of energy contained in a unit of timber volume.

Table 5. "p" values of the multiple comparison test for the period 10 years back
Tabela 5. Wartości „p" testu wielokrotnych porównań dla okresu 10 lat wstecz

Research plot Powierzchnia	Tokarnia	Kornatka	Kamianna
Kornatka	0.60791		
Kamianna	1.00000	1.00000	
Feleczyn	1.00000	**0.02178**	0.47135

KW test: p = 0.0013.

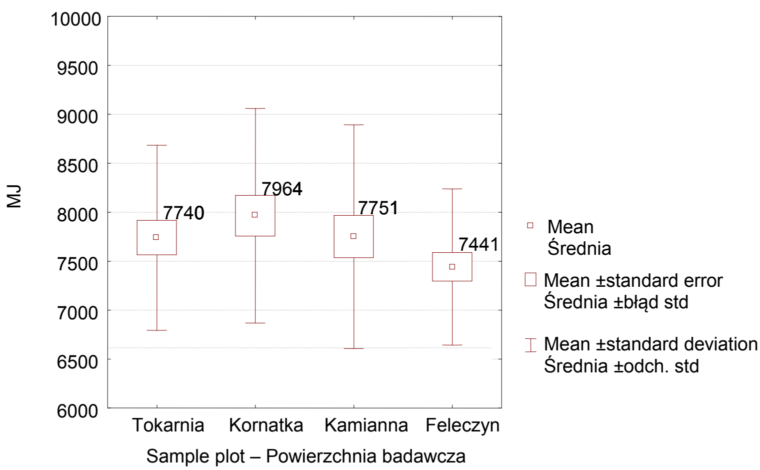

Fig. 3. Average calorific values of 1 m^3 of fir timber for the period 10 years ago
Rys. 3. Średnie wartości ciepła spalania 1 m^3 drewna jodły olbrzymiej w okresie 10 lat wstecz

Table 6. "p" values of the multiple comparison test for the three compared periods
Tabela 6. Wartości „p" testu wielokrotnych porównań dla trzech porównywanych okresów

Period Okres	Current Bieżący	5 years back 5 lat wstecz
5 years back 5 lat wstecz	0.61216	
10 years back 10 lat wstecz	**0.01163**	0.31013

KW test: p = 0.0152.

The present study analyses the heat of combustion of 1 m^3 of giant fir timber, which was calculated as the product of wood density and the heat of combustion of 1 kg of its dry mass, adopted at the level of 20.149 MJ kg^{-1} [Wilson et al. 1987]. It should therefore be noted that the results obtained are subject to certain error.

In this study, the heat of combustion, which would be obtained in the current period from the combustion of 1 m^3 of absolutely dry giant fir timber, amounted to 8021 MJ. Differences in the mean values obtained on particular research plots reached 836 MJ. The significantly higher calorific value of 1 m^3 of timber from Kornatka in relation to trees from Tokarnia and Feleczyn (except for the period 10 years back), is the result of differences in wood density of the examined trees. These differences appear to result from the different trophic character of the habitats in the examined stands. Brown podzolic soils present in the stand in Kornatka are poorer than the brown acid soils present in the other three stands, as indicated by lower values of the trophic factor of these soils [Brożek and Zwydak 2003]. More fertile soils help trees to form wider annual growth rings, which in conifers is generally accompanied by lower wood density [Wąsik 2007, 2010].

Analysing the value of heat of combustion of 1 m^3 of the examined fir timber in the three periods under consideration, it was found that it increases with the age of trees. What points to it are significantly higher mean values obtained for the current period compared to the data from the time when the trees were 10 years younger. The reason for these differences is a lower wood density in young fir trees, which is in direct connection with a high proportion of the juvenile zone on the stem cross-section. The wood of this zone in coniferous species is generally characterized by wider annual increments and lower density. Assuming that the examined giant fir in the juvenile zone has the number of annual increments that is similar to pine, i.e. from 16 to 23 [Jakubowski 2004], one can assume that 10 years ago this zone would have occupied a large cross-sectional area of the stem. This would adversely affect its average wood density and thus also the amount of combustion heat obtained from 1 m^3 of timber. Presumably, in the years to come, the studied fir wood density will increase, as will increase the share of mature timber, characterised by narrower increments and higher density in comparison to the juvenile zone. It seems that it is a high proportion of the juvenile zone in the cross-sections of giant fir tree stems that explains the relatively high values of the obtained coefficients of variability of combustion heat.

The above data may be of interest to purchasers of timber for use as fuel or biofuel of plant origin, such as pellets or briquettes. Assuming that giant fir timber will be offered for sale, it will be more profitable to purchase the timber harvested from older trees, which will be characterised by higher wood density. Consequently, the combustion of such timber will yield more energy; and higher dry matter content per timber volume unit will result in higher yield in the production of pellets or briquettes.

Taking into account the results of this study as well as data, available in forest management plans, concerning the volume of giant fir stands in Kamianna and Feleczyn (for stands in Tokarnia and Kornatka no such data are available), it is possible to calculate the estimated total amount of heat that could currently be obtained from burning the timber of this species, growing in an area of 1 ha. For the stand in Kamianna, for which the volume of giant fir amounts to 300 $m^3 \cdot ha^{-1}$, the total calorific value would now reach 2412 GJ, whereas in the case of the stand in Feleczyn, with the volume of 220 $m^3 \cdot ha^{-1}$ (the stand density index of 1.8), it would be 1686 GJ.

The above data can be compared with the estimated values calculated for the native coniferous species. To that end, we assumed the total volume of the main stand and the subordinate stand of the highest quality classes for the age of 35 years for particular tree species, and additionally in the case of pine – for stronger treatments [Szymkiewicz 2001]. Then, assuming the value of the heat of combustion of 1 kg of dry weight and the average wood density of individual species, given in the literature, we estimated the amount of combustion heat of the large timber of a given species from 1 ha of a stand. Consequently, in accordance with the above, the total volume of the large timber from the main stand and the subordinate stand of pine aged 35 years, of Ia quality class, subject to stronger maintenance treatments, is 267 $m^3 \cdot ha^{-1}$ [Szymkiewicz 2001], timber combustion heat is 20.4 $MJ \cdot kg^{-1}$ [Krzysik 1974 following Wanin and Jesupow], and the average density of absolutely dry wood is 0.490 $g \cdot cm^{-3}$ [Spława-Neyman and Owczarzak 2006]. For the above assumptions, the heat of combustion of large pine timber, obtained from 1 ha of the stand, would amount to 2669 GJ. In the case of silver fir, the assumed values would be, respectively, at the level of 126 $m^3 \cdot ha^{-1}$ [Szymkiewicz 2001], 20.2 $MJ \cdot kg^{-1}$ [Krzysik 1974 following Schlapfer] and 0.410 $g \cdot cm^{-3}$ [Spława-Neyman and Owczarzak 2006], while the total heat of combustion would be 1043 $GJ \cdot ha^{-1}$. For larch, the above values would be, respectively, 252 $m^3 \cdot ha^{-1}$ [Szymkiewicz 2001], 19.9 $MJ \cdot kg^{-1}$ [Krzysik 1974 following Feher], 0.550 $g \cdot cm^{-3}$ [Spława-Neyman and Owczarzak 2006] and 2753 $GJ \cdot ha^{-1}$, while in the case of spruce: 203 $m^3 \cdot ha^{-1}$ [Szymkiewicz 2001], 21.1 $MJ \cdot kg^{-1}$ [Krzysik 1974 following Fabricius], 0.430 $g \cdot cm^{-3}$ [Spława--Neyman and Owczarzak 2006] and 1846 $GJ \cdot ha^{-1}$. It follows, therefore, that the total calorific value of the large timber of giant fir trees aged 35 years, obtained from 1 ha of the stand in Kamianna, would indeed be slightly lower as compared to the corresponding values for pine and larch, but higher as compared to the native silver fir and spruce. This result was mainly affected by a very high stand volume. This indicates a potentially high production capacity of giant fir growing in the climatic conditions of Poland.

One must also mention the extremely strong branch system of the examined tree species, observed during field work in each stand. While reducing the technical quality of stems [Warunki techniczne... 2001], the thick branches occurring on stems practically from the ground upwards constitute an additional amount of biomass that can be used for energy purposes. In addition, dry branches densely occurring on the stem represent a form of protection against damage from animals, which limits the formation of necrosis, and thus reduces the risk of stem rot in the wood [Barszcz 2011]. The appearance of this defect reduces the calorific value of timber.

Given the above, it seems that giant fir can be recommended as a species suitable for the establishment of fast-growing tree plantations to be used for energy purposes.

CONCLUSIONS

Comparative studies of the calorific value of giant fir timber obtained from selected locations of southern Poland allow for the following statements and conclusions:

– The mean calorific value of 1 m^3 of the examined timber of giant fir currently amounts to 8021 MJ; this value for particular research plots ranges from 7662 to 8041 $MJ \cdot m^{-3}$.
– A significantly higher calorific value was noted for 1 m^3 of timber of giant fir trees growing on the poorer soils in Kornatka forest subdistrict as compared to the research plots in Tokarnia and Feleczyn, where the soils were richer.
– The energy value of 1 m^3 of the examined giant fir timber increases with age, which is directly associated with its increasing mean density.
– Given the relatively high stand volume of giant fir that it can obtain in Polish climatic conditions, it seems that this tree species can be recommended as suitable for the establishment of fast-growing tree plantations to be used, inter alia, for energy purposes.

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ANALIZA PORÓWNAWCZA WARTOŚCI ENERGETYCZNEJ DREWNA JODŁY OLBRZYMIEJ (*ABIES GRANDIS* LINDL.) POCHODZĄCEGO Z RÓŻNYCH DRZEWOSTANÓW POLSKI POŁUDNIOWEJ

Streszczenie. W pracy przedstawiono analizę porównawczą wartości ciepła spalania drewna jodły olbrzymiej (*Abies grandis* Lindl.) pochodzącej z czterech drzewostanów Polski południowej. Materiałem badawczym były próbki pobierane w każdym drzewostanie z pni 30 drzew. Próbki dzielono na sekcje zawierające po pięć przyrostów rocznych. Następnie każdej sekcji zmierzono szerokości przyrostów rocznych oraz względną gęstość drewna, którą następnie przeliczono na gęstość bezwzględną, przyjmując całkowity skurcz objętościowy 11%. Założono następnie, że ciepło spalania 1 kg absolutnie suchego drewna jodły olbrzymiej wynosi 20,15 MJ. Na podstawie przeprowadzonych analiz stwierdzono, że średnia wartość ciepła spalania 1 m^3 drewna jodły olbrzymiej wynosi 8021 MJ. Wykazano, że istotnie większą wartość ciepła spalania uzyskano by z 1 m^3 drewna jodły olbrzymiej wzrastającej na glebie uboższej w porównaniu z glebami żyźniejszymi. Analizy statystyczne wykazały również, że wartość ciepła spalania 1 m^3 drewna jodły olbrzymiej istotnie zwiększa się wraz z wiekiem drzew.

Słowa kluczowe: jodła olbrzymia, drewno, ciepło spalania

Accepted for print – Zaakceptowano do druku: 6.08.2012

For citation – Do cytowania: Wąsik R., Michalec K., 2012. Comparative analysis of the calorific value of giant fir timber (Abies grandis Lindl.) from various stands in southern Poland. Acta Sci. Pol., Silv. Colendar. Rat. Ind. Lignar. 11(3), 65-76.