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ENERGY ANALYSIS IN OILSEED PROCESSING INDUSTRY

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SUMMARY. The present study shows the results of research on the variability of energy consumption in oilseed processing plant with an average 24 hour throughput of approximately 160 Mg of rapeseed. The average production of crude oil for 24 hour period amounted to 67 Mg and 39 Mg of refined oil. The variability was defined of the unit electrical and thermal energy consumption indicators. From 289 to 320 kg of oil seeds were processed for the consumption of 1 GJ of energy. The impact of various factors on energy consumption was explained. The results of the present study can be used to define the energy standards as well as to forecast the usage of energy carriers that affect the production cost.

Key words: oilseed processing, energy efficiency, empirical models

LIST OF APPLIED NOMENCLATURE

A_c - 24 hour thermal energy consumption ($A_c = B_{rz} Q_w$), GJ/24 h
A_e - 24 hour of electricity consumption kW·h/24 h
A_{c1} - total energy consumption (including the converter 1kW·h = 12MJ), GJ/24 h
A_{c2} - total energy consumption (including the converter 1kW·h = 3,6MJ), GJ/24 h
B_{ce1} - 24 hour coal equivalent consumption after calculating the value A_{c1}, kg c.e./24 h
B_{ce2} - 24 hour coal equivalent consumption after calculating the value A_{c2}, kg c.e./24 h
B_{rz} - coal consumption, kg/24 h
B_u - 24 hour coal equivalent consumption, Mg c.e./24 h
E_c - energy efficiency of thermal energy consumption, kg of seeds/GJ
E_e - energy efficiency of electrical energy consumption, Mg of seeds/kW·h
E_{c1} - energy efficiency of the total energy consumption (including the converter 1kW·h = 12MJ), kg of seeds /GJ
E_{c2} - energy efficiency of the total energy consumption (including the converter 1kW·h = 3,6MJ), kg of seeds/GJ
K_{rz} - power installed of the electrical equipment per 1000 kg of the oil seeds processed within 24 hours $K_{rz} = P \cdot Z^{-1}$), kW/Mg of seeds
P - total installed power of the electrical equipment, kW
r - coefficient of correlation

R^2 - coefficient of determination,
Q_{ce} - coal equivalent calorific value (29,3076 MJ/kg c.e.),
Q^r_w - coal calorific value, MJ/kg,
W_c - plant indicator of the 24 hour unit thermal energy consumption (W_c=A_c·Z^{-1}), GJ/Mg of seeds,
W_e - plant indicator of the 24 hour unit electrical energy consumption (W_e=A_e·Z^{-1}), kW·h/Mg of seeds,
W_{ce1} - plant indicator of the 24 hour unit coal equivalent consumption including the relation 1 kW·h = 12 MJ, kg c.e./Mg of seeds,
W_{ce2} - plant indicator of the 24 hour coal consumption, including the relation 1 kW·h = 3,6MJ, kg c.e./Mg of seeds,
W_{pc} - plant indicator of the coal equivalent consumption per processed unit, kg of fuel/Mg of seeds,
W_{c1} - plant indicator of the unit total energy consumption (including the calculation 1 kW·h = 12MJ), GJ/Mg of seeds,
W_{c2} - plant indicator of the unit total energy consumption (including the calculation 1 kW·h = 3,6MJ), GJ/Mg of seeds,
Z - 24 hour seeds output, Mg/24 h,
Z_{raf} - 24 hour production of refined oil, Mg/24h,
Z_{sur} - 24 hour production of crude oil, Mg/24h.

INTRODUCTION

Energy efficiency is defined as the quotient of the volume of raw material processing (or a derived product) to the amount of energy carrier used in the production process. It can also be expressed using the unit energy consumption indicators, taking into account the characteristics of a production plant. In the production process, one of the objectives should be to strive for energy efficiency improvements that can be achieved by reducing energy carriers consumption at the stage of their transformation, transmission and final use through changes in technology or organization of production. The conducted rationalization should provide the same or higher level of production. This procedure also results in improving the environmental performance, such as energy conservation, reduced consumption of natural resources, reduced emissions and reduced volume of waste generated at different stages of raw materials processing [WS Atkins Int. 1998]. Oilseeds are used for food and technical purposes intended for heating or production of biofuels [Batchelor et al. 1995, Jóźwiak and Szlęk 2006].

Energy carriers consumption in the oilseed processing plants depends mainly on the size and structure of processing. The quality of raw materials, production technologies, the degree of mechanization of production operations and a capacity utilization rate should be also taken into account [Bargale et al. 1999, Calisir et al. 2005, Ewangelista and Cermak 2007, Kachel-Jakubowska 2009, Panasiewicz et al. 2009, Shkatov et al. 2008, Sobczuk and Tys 2004, Teixeira 2005, Wcisło 2005, 2006, Zheng et al. 2005].

The source of information on the oilseed processing plants energy consumption may be literature data synthesized in Table 1. They are useful for a comparative analysis of plants at different levels of energy carriers usage but do not fully explain the reasons for their variability.

Table 1. Energy consumption in the oilseed processing industry

Directions of energy consumption in the processing plants		Unit energy consumption indicators	Energy efficiency S	Reference scope	Source
Electrical energy	Oil seeds processing	130 kW·h/Mg of seeds	7,69 kg of seeds / kW·h	Z	WS Atkins Int. (1998)
	Refined oil production	290 kW·h/Mg of oil	3,45 kg of oil/kW·h	Z	
	Total (depending on the structure of the rapeseeds output)	48,3 – 212,4 kW·h/Mg of seeds	4,7 – 20,7 kg of seeds / kW·h	Z	Dróżdż and Wojdalski (2001 and 2003)
Thermal energy	Oil seeds processing	3,32 GJ/Mg of seeds	301,2 kg of seeds /GJ	Z	WS Atkins Int. (1998)
	Refined oil production	7,60 GJ/Mg of product	131,6 kg of seeds /GJ	Z	
	Total (depending on the structure of the rapeseeds output)	1,36 – 8,36 GJ/Mg of seeds	119,6 – 735,3 kg of seeds /GJ	Z	Dróżdż and Wojdalski (2001 and 2003)
Coal (excluding the calorific value)	Oil seeds processing	0,1 Mg/Mg of seeds	10,0 Mg of seeds/ Mg of coal	Z	WS Atkins Int. (1998)
	Refined oil production	0,32 Mg/Mg of product	3,1 Mg of seeds/ Mg of coal	Z	
Crude oil production		115 – 170 kW·h/Mg of oil	5,9 – 8,7 kg of seeds / kW·h	Z	Neryng et al. (1990)
Margarine production		45 – 55 kW·h/Mg of product	18,2 – 22,2 kg of seeds/ kW·h	Z	
Extrusion	Electrical energy 1	2 – 24 kW·h/Mg of oil	41,7 – 500,0 kg of oil/kW·h	A	Niewiadomski (1993)
	Electrical energy2	0,28-0,43 kW·h/kg of oil	2,33 – 3,57 kg of oil/kW·h	A	Osiak and Wojdalski (2006)

Extraction department (rapeseeds output)	Steam	300-380 kg/Mg of seeds	2,6 – 3,3 kg of steam/kg of steam	T	Bystram (1986)
	Electrical energy	7-12 kW·h/Mg of seeds	83,3 – 142,9 kg of seeds / kW·h		
	Steam[3]	270 kg/Mg of seeds	3,7 kg of seeds /kg of steam	T	Niewiadomski (1993)
	Steam[4]	410 kg/Mg of seeds	2,4 kg of seeds /kg of steam		
	Electrical energy[3]	62 kW·h/Mg of seeds	16,1 kg of seeds / kW·h		
	Electrical energy[4]	45 kW·h/Mg of seeds	22,2 kg of seeds / kW·h		
Soya oil production	Electrical energy	965 kJ/kg of product	1,02 kg of product/ MJ	P	Hamel (1979)
	Thermal energy	8,885 MJ/kg of product	0,11 kg of product/ MJ	P	
	Total thermal energy	11,12 MJ/kg of product	0,09 kg of product/ MJ	Z	
Peanuts oil production	Electrical energy	546 kJ/kg of product	1,83 kg of product/ MJ	P	Adolfson (1982)
	Thermal energy	1,781 MJ/kg of product	0,56 kg of product/ MJ	P	

Remarks to the table:
[1] – depending on the oil content in the marc (from 50% to 18%)
[2] – oil extrusion from linen seeds with a variable number of screw revolutions and laboratory press nozzle diameter
[3] – extraction with extrusion
[4] – direct extraction
[5] – energy efficiency calculated according to the data contained in the referred source literature
Z – plant scope, P –production scope, T –technological scope (refers to the technological line),
A – unit scope (single equipments and machines).

The research are being made on the usage of preliminary seeds processing in order to increase the oil extraction [Dmitreva et al. 2004, Guderjan et al. 2007, Kartika et al. 2006, Rosenthal et al.

1996, Willems et al. 2009, Zhang et al. 2008]. The detailed results of the research relevant to the efficiency of the different seeds extrusion press work were presented in the following studies: Dafaure et al. 1999a, b, Okoye et al. 2008, Omobuwajo et al. 1999, Owolarafe et al. 2002, Oyinlola et al. 2004, Raji and Favier 2004, Singh and Bargale 2000].

Due to the multi-use oil seeds, it is important to clarify the causes of variability in the output energy consumption. The previously obtained data refer to the summer season. For this reason, research was made during the winter, with outside temperatures from -5 to -10°C. It resulted in the main aim of the study which is to define the energy usage efficiency in a sample oilseed processing plant.

RESEARCH MATERIAL AND METHODOLOGY

The research material comes from oilseed processing plant, that employed in total 343 people (including 101 persons directly involved in production processes) and that was processing on average per day (Z) approximately 160 Mg of rapeseed in the range of 69 to 186 Mg. Daily production included, respectively: crude oil (Z_{sur}) 10-85 Mg and refined oil (Z_{raf}) 16.4 - 59.4 Mg. Installed electrical power (P) was 2374 kW. K_{pr} indicator for 24 hour period ranged between 12.6 and 71.9 kW / Mg of processed rapeseed (on average 13.6 kW / Mg of processed rapeseed). The crude oil production technology for alimentary purposes is presented in the following scheme (graphic 1).

The crude oil production technology for alimentary purposes is presented in the following scheme (Fig. 1).

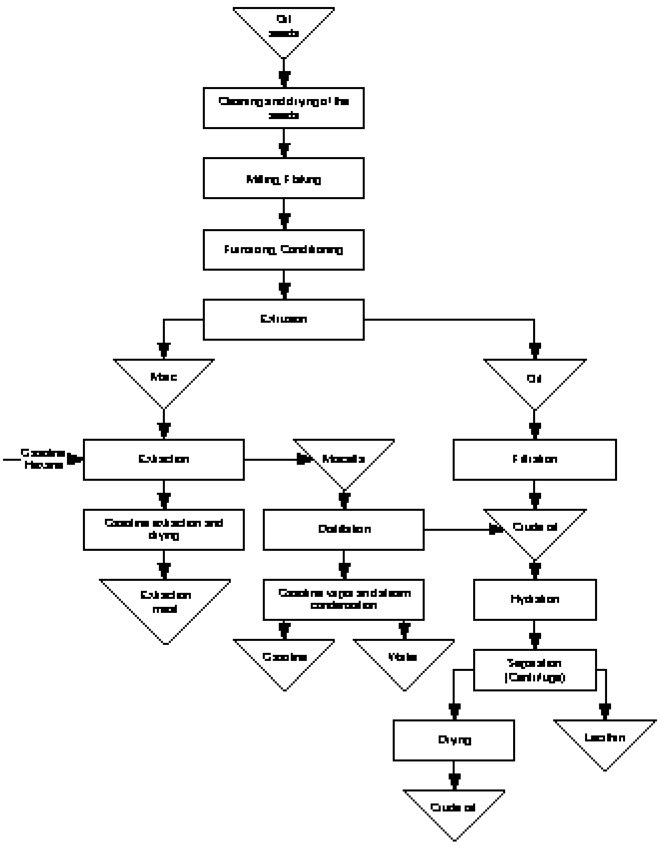

Fig. 1. Technological scheme of crude oil production

The present studies (f. ex. Bystram 1986, Dróżdż and Wojdalski, 2001, 2003, WS Atkins Int. 1998) provide with the tendencies relevant to the energy consumption of these plants. From the evaluation point of view of the determined technology energetic aspects, it is important to apply the indicator value that will embrace the total energy consumption in the processing plant. For this purpose, the following unit energy consumption indicators are applied:

$$W_{r1} = A_1 \cdot Z^{-1} = \left(0{,}012 \cdot A_e + B_{rz} \cdot Q_w^r\right) \cdot Z^{-1} \qquad \text{GJ/Mg of rapeseed,} \qquad (1)$$

$$W_{r2} = A_2 \cdot Z^{-1} = \left(0{,}0036 \cdot A_e + B_{rz} \cdot Q_w^r\right) \cdot Z^{-1} \qquad \text{GJ/Mg of rapeseed.} \qquad (2)$$

In order to fulfill the objective of the present study as well as to detail the so far obtained data, there were calculated the energy efficiency indicators for the different energy categories, based on the following formula:

$$E_n = \frac{Z}{A_n}. \qquad (3)$$

Where: n – refers to the type of energy carrier (electrical energy, thermal energy, total energy).

The above mentioned indicators have been converted into coal equivalent:

$$W_{ce1} = W_{r1}/Q_{ce}, \qquad (4)$$

$$W_{ce2} = W_{r2}/Q_{ce}. \qquad (5)$$

Due to the possibility to use different fuels for generating thermal energy, the exemplary usage for the most common solid biomass was calculated:

$$W_{rz} = \frac{W_c}{Q_w^r}. \qquad (6)$$

In view of the present investigations there was adopted an assumption that the 24 hour rapeseeds' output (Z) has an influence on the energy carriers demand in the fat processing plant. It is not the only factor with a decisive influence on the energy consumption, therefore, there were also analysed the correlations between the production structure, the installed power use indicator (K_{rz}) and the energy consumption of the oilseeds processing plants.

In order to determine the influence of different factors, such as: the value of 24 hour rapeseed output (Z), 24 hour production structure (Z_{sur}, Z_{raf}), the indicator of the installed electrical devices power usage (K_{rz}), on the energy carriers usage (A), being those the real value observed in practice, the following equation was adopted:

$y = b + ax$,

$y = b + a_1x_1 + a_2x_2$,

where: y – explained variable (energy carriers usage, f. ex. A_e, A_c),

x_n – explanatory variables (Z, Z_{sur}, and Z_{raf}, K_{rz}).

The similar procedure was adopted to determine the influence of different factors on the plant unit energy consumption indicators (W_e, W_c, W_{r1}, W_{r2}). The methodological principles of the processing plants energy consumption analysis were presented, among others, in the study of Wojdalski and Dróżdż [2006].

RESULTS AND DISCUSSION

The Table 2 provides with the detailed data describing the energy consumption in the analyzed oilseeds processing plant.

Table 2. Variability of the factors characterizing the analyzed plant energy consumption.

Dependent variable, indicators of energy carriers usage	Symbols and units	Scope	Average
Electrical energy	A_e [kW·h/24 h]	3033–11808	10935
	W_e [kW·h/Mg of seeds]	41,20–196,36	64,79
	E_e [Mg of seeds /kW·h]	5,09 – 24,27	15,43
Thermal energy	A_c [GJ/24h]	113,85–650,90	569,25
	W_c [GJ/Mg of seeds]	3,123,45	3,44
	E_c [kg of seeds /GJ]	289,86 – 320,83	290,45
Total energy	A_{r1} [GJ/24 h]	181,30–786,00	699,44
	W_{r1} [GJ/Mg of seeds]	3,875,81	4,16
	E_{r1} [kg of seeds /GJ]	172,22 – 258,64	240,27
	A_{r2} [GJ/24 h]	137,18–691,43	608,31
	W_{r2} [GJ/Mg of seeds]	3,34–4,16	3,66
	E_{r2} [kg of seeds /GJ]	240,56 – 299,24	273,43
Coal equivalent	B_u [Mg.c.e./24h]	3,88 – 22,21	19,42
	B_{ce1} [Mg c.e./24 h]	6,19 – 26,82	23,87
	W_{ce1} [kg c.e./Mg of seeds]	131,93 – 198,12	142,01
	B_{ce2} [Mg c.e./24 h]	4,68 – 23,59	20,76
	W_{ce2} [kg c.e./Mg of seeds]	114,02 – 141,84	124,79

The statistical analysis of the obtained data resulted in equation of linear regression describing the energy usage variability, that was presented in the Table 3. The scopes of the different empirical formulas application are contained in the Table 2 and in the methodological part of this study.

Table 3. Influence of different technical and technological factors on the energy carriers usage.

Item	Regression equation	r (R²)	Standard estimation error S_e	Nomenclature
1.	$A_e = 4465,86+3,37,67 \cdot Z$ $A_e = 12438,81-113,44 \cdot K_w$ $A_e = 5968,55+10,95 \cdot Z_{tł}+65,20 \cdot Z_{ekstr}$	0,770 (0,592) 0,788 (0,621) 0,714 (0,509)	939,08 904,94 1041,10	A_e [kW·h/24 h] Z [Mg of seeds /24h] K_w [kW/Mg of seeds] $Z_{tł}$ [Mg/24h] Z_{ekstr} [Mg/24h]
2.	$A_c = 5,26+3,312 \cdot Z$ $A_c = 690,17-8,99 \cdot K_w$ $A_c = 119,72 + 2,82 \cdot Z_{tł} + 4,95 \cdot Z_{ekstr}$	0,982 (0,964) 0,906 (0,822) 0,867 (0,751)	19,32 42,80 51,12	A_c – [GJ/24h] Z [Mg of seeds /24h] K_w [kW/Mg of seeds] $Z_{tł}$ [Mg/24h] Z_{ekstr} [Mg/24h]
3.	$A_{r1} = 58,85 + 3,76 \cdot Z$ $A_{r1} = 839,44 - 10,35 \cdot K_w$ $A_{r1} = 191,34 + 2,96 \cdot Z_{tł} + 5,74 \cdot Z_{ekstr}$	0,986 (0,972) 0,922 (0,850) 0,874 (0,764)	19,29 44,36 56,26	A_{r1} – [GJ/24h] Z [Mg of seeds /24h] K_w [kW/Mg of seeds] $Z_{tł}$ [Mg/24h] Z_{ekstr} [Mg/24h]
4.	$A_{r2} = 21,33+3,45 \cdot Z$ $A_{r2} = 734,95-9,40 \cdot K_w$ $A_{r2} = 141,20+2,86 \cdot Z_{tł}+5,19 \cdot Z_{ekstr}$	0,984 (0,969) 0,913 (0,833) 0,870 (0,757)	18,61 42,98 52,40	A_{r2} – [GJ/24h] Z [Mg of seeds /24h] K_w [kW/Mg of seeds] $Z_{tł}$ [Mg/24h] Z_{ekstr} [Mg/24h]
5.	$W_e = 149,41 - 0,501 \cdot Z$ $W_e = 41,91+1,59 \cdot K_w$ $W_e = 124,28 - 0,03 \cdot Z_{tł} - 0,85 \cdot Z_{ekstr}$	0,754 (0,569) 0,814 (0,662) 0,669 (0,448)	13,13 11,62 15,01	W_e – [kW·h/Mg of seeds] Z [Mg of seeds /24h] K_w [kW/Mg of seeds] $Z_{tł}$ [Mg/24h] Z_{ekstr} [Mg/24h]
6.	$W_c = f(Z)$, $W_c = f(K_w)$, $W_c = f(Z_{tł}, Z_{ekstr})$ – inconsiderable regression	–	–	W_c – [GJ/Mg of seeds]
7.	$W_{r1} = 5,25 - 0,0067 \cdot Z$ $W_{r1} = 3,82 + 0,021 \cdot K_w$ $W_{r1} = 4,811 + 0,003 \cdot Z_{tł} - 0,012 \cdot Z_{ekstr}$	0,740 (0,547) 0,797 (0,635) 0,651 (0,424)	0,183 0,164 0,208	W_{r1} – [GJ/Mg of seeds] Z [Mg of seeds /24h] K_w [kW/Mg of seeds] $Z_{tł}$ [Mg/24h] Z_{ekstr} [Mg/24h]
8.	$W_{r2} = 3,994 - 0,003 \cdot Z$ $W_{r2} = 3,465 + 0,008 \cdot K_w$ $W_{r2} = 3,767 + 0,004 \cdot Z_{tł} - 0,005 \cdot Z_{ekstr}$	0,532 (0,283) 0,571 (0,326) 0,486 (0,236)	0,118 0,115 0,124	W_{r2} – [GJ/Mg of seeds] Z [Mg of seeds /24h] K_w [kW/Mg of seeds] $Z_{tł}$ [Mg/24h] Z_{ekstr} [Mg/24h]

Using the regression equations contained in Table 3 we can predict energy carriers consumption according to varying levels of seed processing or production structure. Taking into account the standard error of estimation (Se) we define the average deviation of the results obtained from empirical models, from the actual data. The use of these equations is limited to the range of individual factors variability, since extrapolation of the results is fraught with too much error.

Taking into account the calorific values of different fuels reffered to in the literature [Niedziółka and Zuchniarz, 2006, Rosinski et al. 2006] W_c indicator was recalculated, which resulted in obtaining information on different fuels consumption (constant biomass) assuming the necessary level of thermal energy supplied to the process. The Table 4 shows the results of these calculations, taking into account the calorific values Q_w, expressed in MJ / kg of actual fuel.

Table 4. Indicators of unit energy consumption coming from different fuels

Energy carriers	Calorific value Q_w [MJ/kg]	Indicators of unit fuels consumption W_{rc} [kg of fuel/Mg of seeds]
Hard coal	23,0	149,7
Wheat straw	17,3	199,0
Maize straw	16,8	204,9
Rape straw	15,0	229,5
Sawdust	19,3	178,4
Willow chips	16,5	208,7
Pellets	18,0	191,3
Straw briquettes	17,1	201,3
Wood briquettes	18,0	191,3

Using the data contained in Table 4 we can estimate the amount of various alternative fuels necessary for the production process in case of need to change the energy carrier in order to reduce the plant impact on the environment.

The production volume (Z) naturally affects the level of 24 hour energy consumption. Both the 24 hour thermal energy consumption (A_c) and total energy consumption (A_{r1} and A_{r2}) were explained with the production volume ranging from 96.4 - 97.2%. The indicator of power installed use (K_{m}) similarly affected the 24 hour energy carriers consumption.

The indicator decreases with the increase of raw materials processing, thus affecting the increase of the 24 hour energy consumption. K_{m} indicator affected this consumption from 62 to 85%. Among the unit consumption indicators, the variation W_c is best explained (from 45 to 57%).

It should be remarked that the unit energy consumption indicators contained in Table 2 specify the numerical bands of the corresponding numerical values shown in Table 1. The rapeseed processing efficiency ratios expressed by the indicators E_{r1} and E_{r2} ranged respectively from 172.2 to 258.6 kilograms of seeds / GJ and 240.6 - 299.2 kilograms of seeds/GJ. The value of E_{r2} indicator provides information on the plant energy efficiency, taking into account all energy carriers.

The results of the present study can be used for comparisons with other oilseed processing plants as for specific characteristics resulting from the production technology as well as the applied research methods [Teixeira 2005].

CONCLUSIONS

The analyzed oilseed processing plant was characterized by the unit energy consumption rates similar to those referred in the cited literature. The reasons for the variability of unit energy consumption were explained thoroughly and it turned out that the non production factors were affecting the unit electricity consumption level from 33 to 56%.

The unit thermal energy consumption has not been explained by the independent variables applied. This means the need for fuel and thermal energy rational use. Energy efficiency of heat utilization ranged from 289 to 320 kg of oil seeds/GJ. Studies have shown that it is appropriate to conduct active monitoring as one of the best energy management techniques, in conjunction with the current production volume. The results of the present study may be useful to verify the energy standards as well as the implementation of the cleaner production principles. The obtained indicators may be important to determine the production cost and emission of pollutants into the atmosphere. Moreover, the results of the study provide additional knowledge about the unit consumption of total energy and the possible substitution of fuels (coal) by the energy coming from renewable sources.

The present study provides materials useful for building models of these plants of the industry as energy users as well as the empirical relations between the amount of processing rapeseed and its structure, and the demand for energy carriers.

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EFEKTYWNOŚĆ ZUŻYCIA ENERGII W PRZETWARZANIU NASION OLEISTYCH

Streszczenie. Przedstawiono wyniki badań nad zmiennością zużycia energii w zakładzie przetwórstwa nasion oleistych o średnim przerobie ok. 160 Mg rzepaku w ciągu doby. Średnia produkcja oleju surowego dla okresu dobowego wynosiła 67 Mg oraz 39 Mg oleju rafinowanego. Określono zmienność zakładowych wskaźników jednostkowego zużycia energii elektrycznej i cieplnej. Zużywając 1 GJ energii przetwarzano od 289 do 320 kg nasion oleistych. Wyjaśniono wpływ różnych czynników na zużycie energii. Wyniki zawarte w pracy mogą być wykorzystywane do określania standardów energetycznych oraz prognozowania zużycia nośników energii wpływających na koszty produkcji.

Słowa kluczowe: przetwórstwo nasion oleistych, efektywność energetyczna, modele empiryczne