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FACTORS INFLUENCING ELECTRICAL ENERGY CONSUMPTION IN FRUIT AND VEGETABLES PROCESSING PLANTS

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Key words: fruit and vegetable processing, electric energy consumption, coefficients of electric energy consumption per unit of output

This paper comprises results of research on variability of electrical energy consumption in fruit and vegetables processing plants. The influence of various factors on the electric energy consumption was defined. Some selected causes were explained underlying the variability of a coefficient of electrical energy consumption per unit of output while taking into account adopted technical, technological, and other factors. Empirical formulas were obtained that may be applied in the definition of environmental standards and of best available techniques.

SPECIFICATION OF NOTATIONS USED IN THE PAPER

A_e – active electric energy 24 hrs consumption (kWh / 24h); C – a constant in the mathematical model, e – index exponent in the mathematical model; K_m – installed capacity per 1 Mg of the processed raw material within 24 hrs (kW/Mg); n_1 – number of production workers employed in the plant (people), n_2 – total number of workers employed in the plant (people); P – total installed plant capacity (kW); P_1 – installed capacity of equipment units applied in storage, freezing, and air- conditioning (kW); P_2 – installed capacity of electrical equipment in administrative-social buildings and that of plant lighting (kW); R^2 – coefficient of determination; S_1 – plant buildings development area (sq m); S_2 – total plant area (sq m); t – 24 (h/d); W_e – factory standard per unit electrical energy consumption index (kW h/Mg); Z_1 – 24h/d frozen fruit production volume (Mg/24h); Z_2 – 24h/d frozen vegetables production volume (Mg/24h); Z_3 – 24h/d fruit concentrate production volume (Mg/24h); Z_4 – 24h/d drinkable juices production volume (Mg/24h).

INTRODUCTION

The fruit and vegetable processing branch uses annually more than 6 000 (TJ) and in terms of energy consumption it comes sixth, after sugar, dairy products, meat, fish and baked products branches. At the same time, in the consumption structure of final energy in this branch, 11.6% accounts for electric energy. In some plants, due to the application of refrigeration, the share of electrical energy may amount to more than 50%. The variety of processes and unitary operations, changeable operating conditions and non-simultaneity of installations work, raw materials processing profile and seasonability of production result in high variability in the consumption of electrical energy. Although some publications [Classen, 1992; Grzybek, 2003] present reason-result relationships in energy consumption, yet they do not give a full explanation what factors influence the consumption volume. Coefficients of electrical energy consumption per unit of output presented here are characterized in certain cases by high diversification. It results both from differences in plants' technical equipment and the variability of determination methods of these coefficients.

Although the literature on this subject partially provides variability ranges of processing plant coefficients of electrical energy consumption per unit of output, it does not specify enough factors that may influence their digital value. It can also be presumed from the literature that it is necessary to improve the electrical energy consumption model in fruit and vegetables processing plants. This paper is targeted at an analysis of the hereinabove mentioned problems that may result in the development of models of fruit and vegetables processing plants in their capacity of electrical energy users and in seeking reason-result relationships between adopted independent variables and the use of electrical energy by plants belonging to that branch of industry.

MATERIALS AND METHODS

The materials and measurement methods come from sixteen fruit and vegetables processing plants, which were examined in the summer. The measurements embraced fifty twenty-four-hour periods in each of the plants for which necessary data sets were obtained (detailed research methods

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TABLE 1. Factors influencing electrical energy consumption in the tested processing plants.

Group of factors (Variant)	Meaning, physical sense	Marking applied
I	General characteristic of processing plants tested	P
II	Installed power structure of electrical appliances	P_1, P_2
III	Structure of raw materials or production volume processed daily	Z_1, Z_2, Z_3, Z_4
IV	Coefficients defining technical and technological equipment standard and production processes organization	K_m

Table 1 does not comprise other variables adopted for the testing which turned out to be irrelevant.

were presented in studies by Wojdalski & Dróżdż, [2006] and Lubach [1999]).

Table 1 shows groups of factors (independent variables) influencing electrical energy consumption volume comprising the scope of plant coefficient (definitions of per unit electrical energy and water consumption company indices are contained in study by [Wojdalski *et al*., 1998]).

For this research, the adopted factors (Table 2) were assumed to be decisive in the electrical energy consumption volume in fruit and vegetables processing plants. Statistical analysis was to show impact forces of the adopted independent variables on a selected dependent variable (daily electrical energy consumption A_e and factory coefficients of electrical energy consumption per unit of output – W_e). Taken into account were those reason-result relationships that were limiting the selection of factors to those being a function of certain factors of low relevancy or expressing a tendency adopted at the investment project designing stage. The factors were also adopted in view of their suitability for assessment of the examined processing plants impact on the natural environment and determining the most appropriate techniques available [Kubicki, 1998; Preisner & Pindór, 2000; WS Atkins Int., 1998; Zieńko & Sieńko, 2000].

To explain the *y* dependency on a lot of independent variables (being real parameters observed in practice, or their functions) the following formula was adopted:

$$y = b_0 + b_1x_1 + b_2x_2 + \ldots\ldots + b_kx_k$$

in which *y* is the dependent explained (A_e or W_e); *x* are explaining dependents (*e.g.* P. P_1. K_m).

The application of the empirical formulas received along with the following conditions fulfilled:

$$b_1x_1 + b_2x_2 + \ldots + b_kx_k \geq b_0 \text{ and } x_i \geq 0 \text{ for i } = 1\ldots\text{k}.$$

enables, to a high degree, the explanation of the problem under discussion in the fruit and vegetables processing plants under analysis.

TABLE 2. A characteristic of the examined fruit and vegetables processing plants taking into account selected technical, technological and other factors.

Processing plant	General characteristics of the processing plants			K_m – coefficient for 24 h daily period (kW/Mg)		Coefficient of electrical energy consumption per unit of output W_e (kWh/Mg)	
	Daily throughput of raw materials (Mg)	Production profile*	Total electrical appliances installed power *P* (kW)	Average value	Range	Average value	Range
I	0.1-12.4	1; 2; 3	413	95.0	0.1-412.5	22.0	16.5-27.6
II	1.9-14.0	1; 4	934	167.4	67.0-498.0	314.8	279.7-349.9
III	0.5-137.5	1; 2; 3; 4	1406	177.3	10.2-2812.0	471.9	72.8-871.1
IV	8.7-161.1	3; 4; 5; 6	2294	54.3	14.2-263.9	406.3	341.6-471.0
V	23.8-154.4	2; 3; 6; 8; 10	3528	59.2	22.8-148.5	145.0	127.2-162.7
VI	1.6-622.0	1; 2; 4; 7; 8	5160	250.8	8.6-3175.4	928.8	345.0-1512.5
VII	17.2-83.4	5; 7; 9	5713	141.3	68.5-332.8	915.4	781.3-1049.5
VIII	16.0-484.4	5; 6; 7	6500	62.1	13.4-406.3	431.6	387.5-475.8
IX	0.1-232.9	1; 3; 5; 6; 7; 8	7980	105.6	0.1-1491.6	388.4	158.5-618.2
X	0.1-481.8	1; 5; 7; 8; 10	7992	27.9	0.1-126.8	120.5	105.6-135.5
XI	0.5-351.5	2; 5; 6; 7; 8	8500	182.5	0.1-7929.1	352.7	121.1-1439.7
XII	26.0-398.5	1; 4; 5; 7; 8; 10	10500	76.0	26.4-403.8	256.7	246.9-266.5
XIII	0.1-778.2	5; 6; 7	11792	95.5	0.1-769.3	702.8	494.9-910.7
XIV	0.1-312.3	3; 5; 6; 7; 8	11851	156.7	0.1-2337.5	775.3	471.0-1079.6
XV	0.1-226.9	5; 6; 7; 11	12325	163.1	0.1-4417.6	1462.9	1000.1-1925.7
XVI	0.1-287.9	6; 7; 8; 9	14237	132.4	0.1-1070.5	416.2	256.7-575.69

* Production profile marking: 1 – drinks, 2 – fruit preserves, 3 – vegetable preserves, 4 – other preserves, 5 – frozen fruit, 6 – frozen vegetables, 7 – fruit concentrates, 8 – drinkable juices, 9 – ice-cream, 10 – vegetable concentrates, 11 – dried fruit and vegetables

TABLE 3. Factors affecting the electrical energy consumption variability in processing plants under analysis.

Independent variables group	Regression equations	R^2	Independent variables	
			Marking, dimension	Number range
I	$A_e = 6806.04 + 0.0006 \cdot P^2$	0.635	P (kW)	413-14237
II	$A_e = -45896.0 + 0.0013 \cdot P_1^2 + 29020.5 \cdot \log P_2$	0.708	P_1 (kW) P_2 (kW)	81-6566 35-3588
III	$A_e = 8356.4 + 736.6 \cdot Z_2 + 3468.1 \cdot \sqrt{Z_1} + 13703.4 \cdot \log Z_3 + 1.35 \cdot Z_4^2$	0.630	Z_1 (Mg) Z_2 (Mg)	0.1-282.0 0.7-155.6
	* $A_e = 21798.31 + 730.98 \cdot Z_2 + 281.65 \cdot Z_1$	0.447	Z_3 (Mg) Z_4 (Mg)	0.6-773.0 0.5-312.3
IV	$W_e = 46.7 + 4.12\, K_m$	0.942	K_m(kW/Mg)	9 – 7929

* – equation shape obtained as a result of arresting step-by-step regression procedure, following the introduction of two independent variables

RESULTS AND DISCUSSION

Table 2 represents a characteristics of certain processing plants (volume and structure of daily throughput, total electrical appliances installed power), coefficients K_m expressing the combined degree of the actual use of the daily throughput capacity and of the installed power engagement in the processing of 1 Mg of raw material as well as the processing plant coefficients of electrical energy consumption per unit of output. The processing plants were ranked in ascending order pursuant to the installed electrical appliances power, which shows considerable diversification in technical equipment and the labour share in production processes and the use of refrigeration.

Table 2 shows that in the extreme case the processing plants under analysis differed sixty fold in terms of mean electrical energy consumption per unit of output. Works by [Kubicki, 1998] and [WS Atkins Int., 1998] show that mean yearly electrical energy consumption per unit of output in the fruit and vegetables branch amounted to 720 (kWh/Mg) of raw materials processed and in some of the plants producing thickened apple concentrate this coefficient can be three times lower. The hereinabove mentioned sources also report that the refrigeration branch is the most energy consuming and that in the processing plants under analysis no attention was paid to the need of minimizing electrical energy consumption.

On the ground of the analyses conducted, Table 3 includes empirical formulas expressing the impact of factors comprised in the four adopted groups on electrical energy consumption. In the case of applying factors from group I (Table 1), solely the influence of the total installed power was relevant. Over 60% of variability of the daily electrical energy consumption was attributed to factor P mentioned hereinabove.

Group II is used for the examination of the influence of installed power structure on electrical energy consumption. They imply that variability of the daily electrical energy consumption 70.8% is attributed to the installed power of ammonia refrigerating compressors and devices used in cold storage, sharp freezer storage, and air-conditioning and, to a lesser degree, to consumers in buildings serving administration and social purposes. It is a contribution to the explanation of still little identified electro-energetic management problems concerning those processing plants. Both obtained formulas should be analyzed jointly due to the physical nature of independent variables.

To variables Z_1 and Z_2 (production of frozen fruit and vegetables), Z_3 (production of fruit concentrates) and Z_4 (production of drinkable juice) encompassed by group III, 63% of the impact on the daily electrical energy consumption was attributed. In this respect, based on Singh's work [1986], an exemplary coefficient of technological electrical energy consumption per unit of output can be quoted for the production of canned vegetables, amounting to 200 (kJ/kg). It is more than twenty-five times smaller than analogical coefficient for thermal energy. The production of citric fruit frozen concentrates required the supply of 4047 (kJ/kg) of electrical energy. That coefficient was only twice as small as thermal energy consumption per unit of output.

The use of the IVth group of factors is the source of information about the joint influence exerted on electrical energy consumption by technical and technological factors, by the production operations mechanization degree and by organizational and production factors.

The research results, again, show that installed power P together with coefficient K_m presenting the degree of use of production facilities are of significant importance. That coefficient depends on the daily raw materials processing volume. Due to a large range of variability of coefficient K_m it can be recognized that the received formula is an expression of the cause of changes in energy consumption per unit of output. The research showed that more than 94% of the variability of energy consumption per unit of output is attributed to coefficient K_m. In practice, the formula was proved to be valid when coefficient K_m is smaller than 400 (kW/Mg), *i.e.* in conditions of established and faultless operation, and when the plant employs more than 300 workers in the production area. Maximum processing volume implied a minimum value coefficient K_m.

It should be added that in a season's peak raw material processing volume the maximum installed power use reached 66%. The application of equations obtained is conditioned by the ranges of particular independent variables, and their numerical values are presented in Tables 2 and 3. The obtained empirical formulas including Z_1, Z_2 and P_1 may partly be useful for the analysis of energy-consumption of refrigerated rooms and the choice of refrigerating facilities in the fruit and vegetables processing industry and they are also correlated with the content of work by [Czapp & Charun, 1997] dealing with the energetic balance of a cold storage room. The obtained formulas also enable a thorough analysis in electrical energy management in plants belonging to this branch of industry.

An incomplete explanation of daily electrical energy consumption variability and, simultaneously, considerable variability in terms of areas occupied by the processing plants under examination has led to the development of the following model:

$$A_e = C \cdot P \cdot t\left(\frac{Z}{Z_1 + Z_2} \cdot \frac{S_1}{S_2} \cdot \frac{n_1}{n_2}\right)^e$$

For processing plant IX an exemplary model was obtained:

$$A_e = 0.15 \cdot P \cdot t\left(\frac{Z}{Z_1 + Z_2} \cdot \frac{S_1}{S_2} \cdot \frac{n_1}{n_2}\right)^{0.057}$$

At the same time, the degree of matching of the obtained model to real data averages to 9.5%, and conditions for using the model are as follows:

$n_2 = 800$ (people), $n_1 = 340$ (people),
$S_2 = 4.18 \cdot 10^4$ (m^2), $S_1 = 3.66 \cdot 10^4$ (m^2),
P = 7980 (kW),
$Z \in$ <5; 233> (Mg), $(Z_1+Z_2) \in$ <4; 90> (Mg), t = 24 (h).

It should be emphasized that the model obtained has a limited application and requires improvement by way of taking into account the installed power structure as value P comprises too large a quantity of receivers working during the season. Besides, the model should include the share of installed power in the refrigerating machinery room and refrigeration. Both the obtained model and regression equation take into consideration a larger quantity of variables as compared with works by Rao [1986], Cleland *et al*. [1981], Classen [1992], Gasparino *et al*. [1984], Hackett *et al*. [2005], Jacobs [1981] and Vergara *et al.* [1978]. The hereinabove mentioned authors indicate that models should be separately developed for electrical energy and for thermal energy.

SUMMARY AND CONCLUSIONS

The formulas obtained explain to a high degree the reasons for the variability of daily electrical energy consumption and coefficients of electrical energy consumption per unit of output. They allow the analysis the variability of electrical energy consumption while taking into account relevant technical, technological, and other factors. The detailed results of this work taken into consideration, it can be assumed that the obtained formulas will be useful in the rationalization of power consumption and they may also be useful for the optimization of coefficients of electrical energy consumption per unit of output. It is also of considerable importance for ecological surveys conducted in industrial plants as well as for the preparation of environmental standards.

The research conducted results in the possibility of the development of models of electrical energy consumption per unit of output as well as the optimization of its consumption with, *e.g.,* the use of linear programming.

The research conducted leads to the following conclusions:

1. The daily variability of electrical energy consumption was explained within the range from 44% to 70% by the installed power of the processing plants and the processed material structure.

2. In the differentiation of the coefficient of electrical energy consumption per unit of output, only one factor (K_m) is relevant, which is the function of the power installed and of the daily processed material volume, to which the variability of coefficient W_e is attributed in more than 94%.

3. The collected research material and its analysis were used to determine bases indispensable for the development of a model of a fruit and vegetables processing plant as an electrical energy user.

4. The research results may be useful for the industrial practice since the daily electrical energy consumption level and coefficients of its consumption per unit of output are referred to detailed data characterizing technical equipment of processing plants.

5. The obtained empirical formulas may be useful for forecasting electrical energy consumption in order to define standards of the best available techniques (BAT).

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CZYNNIKI WPŁYWAJĄCE NA ZUŻYCIE ENERGII ELEKTRYCZNEJ W ZAKŁADACH PRZETWÓRSTWA OWOCOWO-WARZYWNEGO

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W pracy zawarto wyniki badań nad zmiennością zużycia energii elektrycznej w zakładach przetwórstwa owocowo-warzywnego. Określono wpływ różnych czynników na zużycie energii elektrycznej. Wyjaśniono wybrane przyczyny zmienności wskaźnika jednostkowego zużycia energii elektrycznej z uwzględnieniem przyjętych czynników technicznych, technologicznych i innych. Otrzymano formuły empiryczne mogące mieć zastosowanie w określaniu standardów środowiskowych i najlepszych dostępnych technik.