TEKA Kom. Mot. Energ. Roln. – OL PAN, 2007, 7, 277–285

FACTORS INFLUENCING ENERGY CONSUMPTION IN FRUIT AND VEGETABLE PROCESSING PLANTS

Janusz Wojdalski, Bogdan Dróżdż, Michał Lubach

Production Engineering Department, Warsaw Agricultural University
Nowoursynowska Str. 166, 02-787 Warsaw, Poland, e-mail: wip koip@sggw.waw.pl

Summary. Results have been presented of research on variability of total energy in fruit and vegetable processing plants. Reasons have been explained for the variability of per unit energy consumption indices taking into account the impact of various technical and technological factors. Per unit fuel and energy consumption indices have been obtained that can be applied in determining environment standards and production costs.

Key words: fruit and vegetable processing industry, production energy consumption, company per unit fuel and energy consumption indices

SPECIFICATION OF DESIGNATION CODES

A_c – heat energy consumption per twenty-four hour period ($A_c = B_{rz} Q_w^r \cdot 10^{-6}$), GJ/24 h
A_e – active electrical energy consumption, kW·h/24 h
A_{t1} – total energy consumption (taking into account conversion factor 1 kW·h = 0.012 GJ), GJ/24 h
A_{t2} – total energy consumption (taking into account conversion factor 1 kW·h = 0.0036 GJ), GJ/24 h
B_{pu} – coal equivalent consumption per twenty-four hour period, kg/24 h
B_{rz} – real fuel consumption, kg/24 h
K_2 – processing plant cubic capacity per_1000 kg (1 Mg) of processed raw material per twenty-four hour period, m^3/Mg
K_m – installed capacity per 1000 kg (1 Mg) of processed raw material per twenty-four hour period, kW/Mg
P – total installed capacity of electrical appliances in the processing plant, kW
P_1 – total installed capacity of electrical appliances in the processing plant boiler-house, hydrophore-room, water treatment station, kW
P_2 – installed capacity of electrical appliances related to fuel storage and transportation, kW
P_3 – installed capacity of electrical appliances used in storage, freezing and air-conditioning (inclusive of ammonia compressors), kW

P_4 – installed capacity of electrical appliances used for the production of prepared food and fruit and vegetable preserves, kW
R^2 – coefficient of determination,
Q_u – calorific value of coal equivalent (0.0293076 GJ/kg),
Q_w^r – calorific value of real fuel, kJ/kg
W_{pu1} – per unit coal equivalent consumption company index, with the inclusion of the relation 1 kW·h = 0.012 GJ, kg of coal equivalent/Mg of raw material processed
W_{pu2} – company index of per unit coal equivalent consumption, with the inclusion of the relation 1 kW·h = 0.0036 GJ, kg of coal equivalent/Mg of raw materials processed
W_{rz1}– company index of per unit real fuel consumption, with the inclusion of the relation 1 kW·h = 0.012 GJ, kg of real fuel/Mg of raw materials processed
W_{rz2}– company index of per unit real fuel consumption, with the inclusion of the relation 1 kW·h = 0.0036 GJ, kg of real fuel/Mg of raw materials processed
W_{t1} – company index of total per unit fuel consumption, with the inclusion of the relation 1 kW·h = 0.012 GJ, GJ/Mg of raw materials processed
W_{t2} – company index of total per unit fuel consumption, with the inclusion of the relation 1 kW·h = 0.0036 GJ, GJ/Mg of raw materials processed
Z – processing of raw materials in twenty-four hour period, Mg/24 h
Z_1 – frozen vegetables production volume, Mg/24 h
Z_2 – fruit concentrates production volume, Mg/24 h
Z_3 – fruit juice production volume, Mg/24 h
Z_4 – beverage production volume, Mg/24 h

INTRODUCTION

Most frequently, subject literature sources report results of energy consumption research with regard to selected production lines or to specific energy carriers. In industrial production and its effects on the natural environment it is also necessary to determine a joint consumption of energy carriers inclusive of alternative ones, and also seeking solutions resulting in a reduction of pollution emission into the environment.

Both energy consumption and its patterns in individual processing plants are dependent on the following factors: seasonability in production, production technology, diversity of periodically applied processes and unit operations, multidirectional raw material processing (processing structure), changeable service conditions and absence of simultaneity in service duty. The energy consumption patterns in individual plants in this industry branch also differ from one another depending on the proportion of heat treatment applied and on the application of refrigeration and freezing [Singh 1986, Wojdalski *et al.* 1993, and Hackett *et al*. 2005]. For example, papers published by Classen [1992] and Grzybek [2003] do not fully explain what factors affect energy consumption volume of entire processing plants inclusive of aggregate energy consumption. Up to date publications by Wojdalski *et al.* [2006a and b] provide separate explanations for reasons of variability in electrical and heat energy consumption. Per unit consumption of individual energy carriers differs depending on production technology and processing plant technical equipment. There is also a large variability of per unit consumption of heat and electrical energy and cooling water, e.g. during the production of thickened apple juice which arises from Kowalczyk's paper [2006].

In the subject literature, no variability ranges have been found of plant per unit energy consumption indices comprising the grand total of electrical and heat energy, the latter being factors that might also affect numerical value thereof.

The target of this paper is to modify the up-to-date applied methods of production energy consumption analysis by the inclusion of indices of primary per unit energy consumption as converted into coal/oil equivalent and into real fuel, especially from renewable sources. Besides, one of the targets of this paper is to provide materials helpful in the construction of models of plants in this industry in the capacity of energy users as well as to seek relationships between assumed independent variables and a demand for energy supplied in the form of various fuels.

MATERIAL AND METHODOLOGY

Materials and measurement results from 16 fruit and vegetable processing plants were collected in the summer season. The measurements in each of the plants for which necessary data sets were obtained comprised fifty twenty-four-hour periods. Detailed research methods can be found in papers published by Wojdalski and Dróżdż [2006], and by Lubach [1999]. Definitions of company per unit energy consumption indices are included in Wojdalski *et al.* [1998].

Table 1 includes factor groups (independent variables) affecting the total energy consumption at a company index level.

Table 1. Factors conditioning energy consumption in the examined processing plants

Factors analysed		A physical sense, importance for the conducted analyses
Group (Variant)	Designation codes applied	
I	Z, P	A general characteristic of the processing plants
II	P_1, P_2, P_3, P_4	The structure of the installed capacity in electrical devices used in the processing plants
III	Z_1, Z_2, Z_3, Z_4	The structure of 24-hour throughput or the structure of production (manufacturing profile)
IV	K_2	Indices representing the technical and technological equipment level, the manufacturing process organization level, and the land development level

Table 1 comprises only those variables which were found to be relevant in the conducted research.

Papers published up to this date have presented solely heat or electrical energy consumption. It should be pointed out that in terms of costs and the choice of a specific technology it is important to employ the concept of cumulative product energy consumption or an index that would comprise aggregate energy consumption both in a processing plant and after conversion into primary energy. For this aim the following per unit energy consumption indices were adopted:

$$W_{t1} = \frac{A_{t1}}{Z} = \frac{0.012 \cdot A_e + B_{rz} \cdot Q_w^r \cdot 10^{-6}}{Z} \quad \text{GJ/Mg}$$

$$W_{t2} = \frac{A_{t2}}{Z} = \frac{0.0036 \cdot A_e + B_{rz} \cdot Q_w^r \cdot 10^{-6}}{Z} \quad \text{GJ/Mg}$$

The herein above presented indices were converted into coal equivalent and into real fuel, based on the following formulas:

$$W_{pu1} = W_{t1}/Q_u\,, \quad W_{rz1} = W_{t1}/\,Q_w^r$$

$$W_{pu2} = W_{t2}/Q_u, \quad W_{rz2} = W_{t2}/\,Q_w^r$$

Table 2. A characteristic of the examined fruit and vegetable processing plants taking into account selected technical and technological factors

Processing plant	General characteristic of the plants			Mean indices of per unit energy consumption for a 24-hour period			
	Max. 24-hour raw material throughput Z, Mg	Production profile*	Mean value of K_m factor per 24-hour period kW/Mg	Aggregate energy consumption GJ/Mg		Coal equivalent kg/Mg	
				W_{t1}	W_{t2}	W_{pu1}	W_{pu2}
I	12.4	1; 2; 3	95.0	4.70	4.52	160.4	154.2
II	14.0	1; 4	167.4	19.14	16.49	653.1	562.6
III	137.5	1; 2; 3; 4	177.3	5.87	1.91	200.3	65.2
IV	161.1	3; 4; 5; 6	54.3	5.08	1.66	173.3	56.6
V	154.4	2; 3; 6; 8; 10	59.2	11.92	10.70	406.7	365.1
VI	622.0	1; 2; 4; 7; 8	250.8	11.60	3.80	395.8	129.7
VII	83.4	5; 7; 9	141.3	16.03	8.34	546.9	284.6
VIII	484.4	5; 6; 7	62.1	5.48	1.86	187.0	63.5
IX	232.9	1; 3; 5; 6; 7; 8	105.6	20.45	17.90	697.8	610.8
X	481.8	1; 5; 7; 8; 10	27.9	5.64	4.63	192.4	158.0
XI	351.5	2; 5; 6; 7; 8	182.5	22.36	12.84	762.9	438.1
XII	398.5	1; 4; 5; 7; 8; 10	76.0	11.62	9.46	396.5	322.8
XIII	778.2	5; 6; 7	95.5	13.69	7.79	467.1	265.8
XIV	312.3	3; 5; 6; 7; 8	156.7	17.39	10.88	593.4	371.2
XV	226.9	5; 6; 7; 11	163.1	24.26	11.97	827.8	408.4
XVI	287.9	6; 7; 8; 9	132.4	10.61	7.12	362.0	242.9

* production profile designations: 1 – beverages, 2 – fruit preserves, 3 – vegetable preserves, 4 – other preserves, 5 – frozen fruit, 6 – frozen vegetables, 7 – fruit concentrates, 8 – juices, 9 – ice-cream, 10 – vegetable concentrates, 11 – dried fruit and vegetables.

An assumption was made that the adopted factors (Table 1) as well as others specified in the detailed research method [Wojdalski and Dróżdż 2006] affect the aggregate energy consumption in the processing plants. Those factors were also adopted on account of their usefulness for the assessment of the effect the processing plants exert on the environment and determination of the best available techniques [Kubicki 1998, WS Atkins Int. 1998, Wojdalski and Dróżdż 2004].

In order to explain dependence of Y on a lot of independent variables (the real values observed in practice or their functions), an equation was adopted:

$$Y = a_0 + a_1x_1 + a_2x_2 + ...+a_kx_k$$

where:

Y – variables under explanation (A_{t1}, A_{t2}, W_{t1}, W_{t2}),
x – explaining variables (e.g. K_2, P, P_1, P_2, P_3, P_4, Z, Z_1, Z_2, Z_3, Z_4).

Once the following conditions are met:

$$a_1x_1 + a_2x_2 +.....+a_kx_k \geq a_0 \text{ and } x_i \geq 0 \text{ for } i = 1....k.$$

the application of resulting regression equations and taking into account correlation and determination coefficients (r i R^2) enables partial explanation of the subject under discussion in the analyzed fruit and vegetable processing plants.

RESULTS

The obtained results make it possible to seek cause and effect relationships between the 24-hour-period production volume of the fruit and vegetable processing plants and the consumption of primary energy carriers. Table 2 presents data regarding processing plants (maximum raw materials throughput volume and structure per 24-hour-period, K_m indices representing the extent to which throughput capacity and installed capacity are used in the throughput of 1 Mg of raw material as well as company indices of per unit primary energy and coal equivalent consumption. The herein presented data indicate that the processing plants differ significantly in terms of their technical equipment. In the analyzed plants, values of mean total per unit energy consumption and of coal equivalent consumption considerably differed from one another and were dependent on the throughput structure. The smallest values of per unit energy consumption and coal equivalent consumption were found in those plants where refrigeration and freezing represented a large proportion of production technology.

Table 3 comprises regression equations representing the effect that factors included in the four adopted groups exerted on the aggregate energy consumption. Only those equations were presented where the correlation coefficient was greater than 0.7. Taking into account the first factor group (Table 1) it can be seen that only the effect of the production volume per 24-hour-period and that of the plants' total installed capacity were relevant. The correlation coefficient (r) between the variables exceeded 0.74.

Variables Group II (Table 1) served to show relationships between the installed capacity structure and the aggregate energy consumption. The research showed that the 24-hour energy consumption variability expressed as A_{t1} quantity was attributed in 66.6% to the installed capacity of devices employed in storage, freezing and air-conditioning (inclusive of ammonia compressors) and electrical devices used in the production of ready-made food and fruit and vegetable preserves. The increase in energy consumption expressed by the A_{t2} equation depends mainly on the installed capacity of electrical appliances in the company boiler house, hydrophore room and water treatment station.

Table 3. Factors affecting variability of aggregate energy consumption in the examined processing plants

Independent variables group	Equation	R^2	Independent variables	
			designation, unit of measurement	numeric range
I	A_{t1}= -140.22 + 2.03·Z +0.11·P	0.762	P, kW Z Mg	413–14237 12.4–778.2
	A_{t2} = -266.74 + 1.53· Z + 8.02 · $\sqrt{P}$	0.556		
II	A_{t1}= 287.8 + 0.26 · P_3 – 430.0/P_4	0.666	P_1, kW P_2, kW P_3, kW P_4, kW	41–1715 3–220 81–6566 30–3178
	A_{t2} = - 182.6 + 35.06 · $\sqrt{P_1}$ - 0.02· P_2^2	0.617		
III	A_{t1}= 401.9 + 0.06 Z_1^2 +449.89·logZ_2+315.28·log Z_3	0.594	Z_1, Mg Z_2, Mg Z_3, Mg Z_4, Mg	0.1–282.0 0.6–773.0 0.5–312.3 0.8–191.1
	A_{t2} = 480.5+4.25 Z_4+327.79·log Z_2 - 280/Z_3	0.639		
IV	W_{t1} = - 0.06 + 0.0026 K_2	0.904	K_2, m^3/Mg	307–307692
	W_{t2} = - 0.29 + 0.0018 K_2	0.898		

Over 59.4% of the effect exerted on the aggregate energy consumption per 24-hour-period represented by the quantity A_{t1} was attributed to quantities Z_1 (production of frozen vegetables), Z_2 (production of fruit concentrates) and Z_3 (production of juices) comprised in Group III. The introduction of quantity Z_4 (production of beverages) in the A_{t2} equation resulted in an increase of R^2 value to 0.639.

Group IV, the last one, supplies results proving that the per unit energy consumption index W_{t1} was strongly correlated with the K_2 quantity, since the correlation coefficient amounted to over 0.95. Coefficient r = 0.947, not much smaller, was obtained for the equation representing variability of W_{t2} index, i.e. the aggregate per unit energy consumption for the whole processing plant. The results obtained herein confirm a tendency resulting from variant I of a strong effect of the cubic capacity of production rooms on the index of aggregate energy consumption [Wojdalski *et al*., 2006a]. The K_2 index in the equation (Table 3) is the function of the total processing plant cubic capacity and of the throughput in 24-hour period. The resulting equation has the highest usability in conditions of well-established and faultless operation, when K_2 ranges from 1900 to 9300 m^3/Mg.

The application of the resulting equations requires taking the ranges into account (Tables 2 and 3).

The resulting equations include a larger number of variables as compared with results of research work conducted by Classen [1992] and Singh [1986] wherein energy consumption was analyzed in fruit and vegetable processing industry.

Taking into consideration calorific values of various fuels included in the subject literature [Niedziółka and Zuchniarz 2006, Rosiński *et al*. 2006], Table 4 presents the consumption of energy carriers (real fuel) as a result of converting indices W_{t1} and W_{t2}. For the calculations, calorific values Q_w^r expressed in GJ/kg of real fuel were applied. The calculation results regard processing plant V (Table 3) for which the per unit energy consumption index W_{t1} = 10.92 GJ/Mg and which is near-arithmetic average for the group of processing plants under examination.

Table 4. Per unit energy carrier consumption indices for processing plant V

Energy carriers	Calorific value Q_w^r, MJ/kg	Per unit fuel consumption indices	
		W_{rz1} kg/Mg of raw material processed	W_{rz2} kg/Mg of raw material processed
Lignite	14.0	851.4	764.3
Hard coal	26.0	458.5	411.5
Natural Gas	32.0	372.5	334.4
Fuel Oil	42.6	279.8	251.2
Used Engine Oil	41.5	287.2	257.8
Vegetable Oil	37.5	317.8	285.3
Inflammable Waste	37.2	320.4	287.6
Wheat Straw	17.3	689.0	618.5
Barley Straw	16.1	740.4	664.6
Maize Straw	16.8	709.5	636.9
Colza Straw	15.0	794.7	713.3
Wood Dust	17.0	701.2	629.4
Sawdust	19.3	617.6	554.4
Willow Chips	16.5	722.4	648.5
Pellets	18.0	662.2	594.4
Straw Briquettes	17.1	697.1	625.7
Wood Briquettes	18.0	662.2	594.4

CONCLUSIONS

The presented results represent a progress with respect to results comprised in the quoted subject literature sources. To a greater extent than before reasons for the variability of the aggregate energy consumption per 24-hours were explained, having taken into account a number of technical and technological factors. The resulting equations may come useful for the monitoring of energy input and optimization of the aggregate per unit energy consumption indices. These results may also have importance in ecological surveys conducted in industrial plants aimed at the determination of environmental standards.

Energy consumption levels of industrial plants with similar production profile differ from one another a few times which proves that there are possibilities of enhancing production efficiency and decreasing emission of gas pollutants into the environment.

The research results also lead to the following conclusions:

1. The variability range from 55.6 to 76.2% of 24-hour energy consumption level was explained by a plant's total installed capacity and the volume of its 24-hour throughput.
2. The most useful factor in providing explanation for variability of aggregate per unit energy consumption indices per a raw material unit of throughput is (K_2) factor which is a function of the plant's total volume capacity and 24-hour throughput, and to which ca. 90 % of variability of fuel and energy consumption indices W_{pu1}, W_{pu2}, W_{t1} i W_{t2} were attributed.
3. The aggregate 24-hour energy consumption level and its per unit consumption indices are referred to data defining production structure and technical equipment of processing plants and, partly, to land development; for these reasons the research results can be found useful in industrial practice.
4. The resulting equations partly contribute to supplying explanation to rather poorly investigated problems in this respect and can be used with the view of defining standards of the best available techniques and energy saving by plants applying for the issuance of integrated permits as well as defining production costs when an energy carrier is substituted.

The results presented herein constitute a supplement to the knowledge comprised in Grzybek's study [2003]. Besides, they are correlated with the work of Hackett *et al.* [2005] including energy saving calculation results for seven plants of different sizes.

REFERENCES

Classen J. 1992: Processing Energy Requirements for Several Vegetables. Trans. ASEA, 35(3), 973–974.

Grzybek A. 2003: Wpływ wybranych technologii na środowisko i energochłonność przetwórstwa owocowo-warzywnego. Rozprawy habilitacyjne nr 12. Inż. Roln. 2 (44).

Hackett B., Chow S., Ganji A.R. 2005: Energy Efficiency Opportunities in Fresh and Vegetable Processing/Cold Storage Facilities. Paper presented in the 2005 ACEEE Summer Study on Energy Efficiency in Industry, July 19–22. West Point, NY.

Kowalczyk R. 2006: Analiza technologiczno-techniczna produkcji zagęszczonego soku jabłkowego. Rozprawy Naukowe i Monografie. SGGW, Warszawa.

Kubicki M. (red.) 1998: Ochrona środowiska w przemyśle owocowo-warzywnym. Wyd. FAPA, Warszawa, 30–36, 38–43.

Lubach M. 1999: Wpływ wybranych czynników na energochłonność zakładów przemysłu owocowo-warzywnego. Rozprawa doktorska. SGGW, Warszawa.

Niedziółka I., Zuchniarz A. 2006. Analiza energetyczna wybranych rodzajów biomasy pochodzenia roślinnego. MOTROL, Motoryzacja i Energetyka Rolnictwa. Lublin, tom 8A, 232–237.

Rosiński M., Furtak L., Łuksa A., Stępień A. 2006: Wykorzystanie olejów roślinnych i urządzeń do spalania w procesach suszarniczych. MOTROL, Motoryzacja i Energetyka Rolnictwa. PAN Lublin, t. 8A, 243–250,

Singh R.P. 1986: Energy Accounting of Food Processing Operations (in Energy in Food Processing). Elsevier, Amsterdam – Oxford – New York – Tokyo, 33, 36.

Wojdalski J., Domagała A., Kaleta A., Janus P. 1998: Energia i jej użytkowanie w przemyśle rolno-spożywczym. SGGW, Warszawa, 10–11.

Wojdalski J., Dróżdż B. 2006: Podstawy analizy energochłonności produkcji zakładów przemysłu rolno-spożywczego. MOTROL, Motoryzacja i Energetyka Rolnictwa. Lublin, t. 8A, 294–304.

Wojdalski J., Dróżdż B., Lubach M. 2006a: Uwarunkowania gospodarki cieplnej w zakładach przetwórstwa owocowo-warzywnego. MOTROL, Motoryzacja i Energetyka Rolnictwa PAN Lublin, t. 8A, 286–293.

Wojdalski J., Dróżdż B., Lubach M. 2006b: Factors Influencing Electrical Energy Consumption in Fruit and Vegetables Processing Plants. CIGR International Symposium, Warsaw. 2nd Technical Symposium of CIGR Section VI. XII BEMS 2006 (12th National Symposium on Food Engineering). Collection of Extent Abstracts, Warsaw, 26–28 April 2006, 243.

Wojdalski J., Grzybek A., Rogulska M. 1993: Struktura i możliwości racjonalizacji zużycia energii w zakładach przemysłu owocowo-warzywnego. Przem. Ferment. i Owoc.-Warz., 3, 12–16.

WS Atkins International 1998: Ochrona środowiska w przemyśle rolno-spożywczym. Standardy środowiskowe. FAPA, Warszawa, 66–69, 107.