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EFFECTIVENESS OF ELECTRICAL ENERGY AND WATER CONSUMPTION IN A SMALL-SIZE DAIRY PROCESSING PLANT

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Summary. Results have been presented of research on variability of electrical energy and water consumption in a small-size dairy processing plant. Variability of per unit electrical energy and water consumption factory indices was explained while taking into account an impact of twenty-four hour processed milk volume. The indices obtained per unit consumption may be used to define environmental standards as well as eco-effectiveness and manufacturing costs.

Key words: dairy industry, electrical energy consumption, level of manufacturing, electrical energy and water consumption factory indices, eco-effectiveness.

SPECIFICATION OF LETTER SYMBOLS APPLIED IN THIS PAPER

A - energy carrier consumption,
A_c - monthly thermal energy consumption ($A_c = B_{rz} Q^r_w \cdot 10^{-6}$), GJ/month,
A_e - monthly active electrical energy consumption, in kW·h / month,
A_{t1} - total energy consumption (taking into account converter 1 kW·h = 0.012GJ), GJ/month,
A_{t2} - total energy consumption (taking into account converter 1 kW·h = 0.0036GJ), GJ/month,
A_w - total water consumption, m^3/month,
B_{rz} - consumption of real fuel kg/month,
K_m - installed power of electrical appliances per 1000 l of processed milk in twenty-four hours ($K_m = P \cdot Z_d^{-1}$) kW/1000 l,
P - installed power of electrical appliances, in kW,
R - correlation coefficient,
R^2 - determination coefficient (r^2),
Q_u - calorific value of ton of oil equivalent (0.0293076 GJ/kg per unit),
Q^r_w - calorific value of real fuel MJ/kg, GJ/kg,
W_c - factory per-manufactured-unit coefficient of thermal energy consumption for a period of one month, MJ/1000 l.

W_e - factory per-manufactured-unit coefficient of electrical energy consumption for a period of one month, kW·h/1000 l,
W_{pu1} - factory per-manufactured-unit coefficient of consumption of a kg of coal equivalent, taking into account 1kW·h = 0.012 GJ, kg of c.e./1000 l ratio,
W_{pu2} - factory per-manufactured-unit coefficient of consumption of a kg of coal equivalent, taking into account 1 kW·h = 0.0036GJ, kg of c.e./1000 l ratio,
W_{rz1} - factory per-manufactured-unit coefficient of consumption of total energy contained in real fuel (taking into account 1kW·h = 0.012 GJ conversion), MJ/1000 l,
W_{rz2} - factory per-manufactured-unit coefficient of consumption of total energy contained in real fuel (taking into account 1kW·h = 0.0036 GJ conversion), MJ/1000 l.
W_{t1} - factory per-manufactured-unit coefficient of consumption of total energy (taking into account 1kW·h = 0.012 GJ conversion), MJ/1000 l,
W_{t2} - factory per-manufactured-unit coefficient of consumption of total energy (taking into account 1kW·h = 0.0036 GJ conversion), MJ/1000 l,
W_w - factory per-manufactured-unit coefficient of water consumption for a period of one month ($W_w = A_w \cdot Z^{-1}$), m^3/1000 l,
Z - monthly throughput of milk, in thousand litres,
Z_d - milk throughput in twenty-four hours, in thousand litres.

INTRODUCTION

Effectiveness is defined as a result of economic (industrial) activity as being a quotient of the effect obtained to the outlay. One way of expressing it is manufacturing energy consumption i.e. the demand for energy to carry out a specific manufacturing process. Energy effectiveness can be defined as a decrease in energy consumption which takes place at the stage of manufacturing (transformation), transmitting, distributing or final use under the influence of changes in technology, ensuring the same or a higher manufacturing or services level. It is closely connected with eco-effectiveness consisting in reaching high environmental effects which consist in a decrease in the use of natural resources, reduction of emission of environment polluting substances and a decrease in the weight of the produced waste [Prasad et al., 2004].

The energy carriers consumption in dairy processing plants depends on numerous factors from amongst which as the most common the following ones are mentioned: the type of plant, throughput volume and structure, the mechanization degree of production processes and the degree of use of its manufacturing capacity [Kaleta and Wojdalski 2007, Wojdalski and Dróżdż 2001].The type and quantities of the used energy carriers are allowed for in the integrated license representing a collection of requirements and principles aimed at effective environment protection in pursuance of requirements of the best manufacturing technique available [Bosworth et al., 2000, WS Atkins – Poland, 2005].

Although the problems touched on hereinabove are dealt with in such sample publications as IFC – World Bank Group [2007], Ramirez et al. [2006], Walton [2007], Wardrop Engineering Inc. [1997], Wojdalski et al. [2002], WS Atkins Int. [1998], yet the reasons for energy carriers variability in processing plants of different sizes have not been fully accounted for.

The objective of this paper was to determine the effectiveness of energy and water management in a small-size dairy processing plant. Besides, this paper was meant to supply materials helpful in the constructing in this industry plant of models such as energy users and seeking relations between an adopted independent variable and the demand for energy carriers which may constitute a component of manufacturing eco-effectiveness.

MATERIAL AND METHODOLOGY

Material for study was collected in a dairy plant which, on average, in twenty-four hours processes Z_d of ca. thirty thousand litres of milk into the following production range: consumer milk in plastic bags, cottage cheese and butter. Monthly milk throughput volumes rang within the limits from 604,580 to 960,240 litres (on average 796,400 litres). The total installed power of plant P electrical appliances amount to 94 kW. A mean value of the K_m coefficient for the twenty-four hour period amounts to 3.03 kW/1000 l. For the implementation of the objective of this paper the authors used a model of a food processing plant as an energy carrier user and a factory per-manufactured-unit coefficient of electrical energy and water consumption as defined by a method presented in Wojdalski and Dróżdż publication [2006].

Studies published up to date have most frequently presented thermal or electrical energy consumption on a separate basis. It should be pointed out that from the point of view of costs and selection of a specified technology, it is important to use product accumulated energy consumption level or a coefficient that would comprise total energy consumption both in the processing plant and expressed in original energy. For this end the following factory per-manufactured-unit coefficients of electrical energy consumption were adopted:

$$W_{t1} = \frac{A_{t1}}{Z} = \frac{0{,}012 \cdot A_e + B_{rz} \cdot Q_w^r \cdot 10^{-6}}{Z} \quad \text{GJ/1000 l of milk},$$

$$W_{t2} = \frac{A_{t2}}{Z} = \frac{0{,}0036 \cdot A_e + B_{rz} \cdot Q_w^r \cdot 10^{-6}}{Z} \quad \text{GJ/1000 l of milk}.$$

The above-mentioned coefficients were expressed in t.o.e. (ton of oil equivalent) and in real fuel by applying the following formulas:

$$W_{pu1} = W_{t1}/Q_u = 3412{,}08 \cdot 10^{-2} W_{t1},$$
$$W_{pu2} = W_{t2}/Q_u = 3412{,}08 \cdot 10^{-2} W_{t2}.$$

At the same time the coefficients were expressed in energy that may be obtained from e.g. renewable sources, by applying the following formulas:

$$W_{rz1} = W_{t1}/Q_w^r,$$
$$W_{rz2} = W_{t2}/Q_w^r.$$

An assumption was made that a twenty-four hour milk throughput volume affects energy carriers' wear in a processing plant. That factor was adopted due to its utmost utility for the assessment of an impact that the processing plants in this industry have on the environment and the possibility of determining the best manufacturing techniques available [Wojdalski and Dróżdż 2004, WS Atkins Int. 1998].

In order to explain the dependence between an energy carrier wear (A) and the independent variable (Z) – the latter being a real value observed in practice, the equation was adopted:

$$A = b + aZ.$$

Wherein: A – energy carriers wear (variable explained – W_e, W_c, W_w), Z – the manufacturing volume (explaining variable).

With those conditions fulfilled:

$$aZ \geq b \text{ and } Z \geq 0,$$

an application of obtained regression equations allowing for correlation and determination coefficients (r and R^2) enables one to partly explain the problem under discussion in the analyzed production plant of the dairy industry.

RESULTS AND DISCUSSION

Table 1 presents variability ranges of energy carriers wear within the period of one year.

Table 1. Annual use of energy and water carriers allowing for milk throughput volume

Dependent Variable, wear coefficient	Season of the year	Range	Average
Electrical Energy W_e [kW·h/1000 l]	Summer	45.31-68.79	67.41
	Winter	70.21-83.20	
Thermal Energy W_c [MJ/1000 l]	Summer	1374.65-1736.31	2233.78
	Winter	2784.05-3274.98	
Total Energy W_{t1} [GJ/1000l]	Summer	1.93-2.47	3.04
	Winter	3.63-4.19	
Total Energy W_{t2} [GJ/1000l]	Summer	1.40-1.96	2.46
	Winter	3.04-3.55	
Fuel c.e. W_{pu1} [kg/1000 l]	Summer	66-84	104
	Winter	124-143	
Fuel c.e. W_{pu2} [kg/1000 l]	Summer	48-67	84
	Winter	103-121	
Power Coefficient cosφ	Summer	0.813-0.815	0.813
	Winter	0.800-0.816	
Water W_w [m³/1000 l]	Summer	2.43-2.78	2.83
	Winter	2.96-3.18	

The average factory per-manufactured-unit electrical energy consumption W_e (Table 1) in particular months showed seasonal fluctuations in excess of 80%.

The factory per-manufactured-unit thermal energy consumption W_c in extreme cases differed from one another by 2.4 times. The factory per-manufactured-unit water consumption showed the lowest diversification (ca 16%).

Adopting one-month periods, equations were obtained expressing variability of factory per-manufactured-unit electrical energy and water consumption coefficients presented in Table 2.

Table 2. The effect of monthly milk throughput on the per-manufactured-unit energy carriers consumption

Regression Equation	Correlation Coefficient r
$W_e = 114.87 - 0.0596 \cdot Z$	0.741
$W_c = 6690.1 - 5.596 \cdot Z$	0.970
$W_w = 4.3604 - 0.0019 \cdot Z$	0.905

The milk throughput volume affected in 55% the factory per-manufactured-unit electrical energy consumption while the variability of the factory per-manufactured-unit thermal energy consumption in 94%. It was also proved that the variability of water consumption was conditioned by the throughput volume in 82%.

It results from the conducted research that the factory per-manufactured-unit electrical energy consumption was greater than in other plants with the same production throughput profile and similar installed power of electrical appliances. It was also indicated that, adopting two-twenty-four hours' periods for the purpose of this study, the milk throughput volume did not substantially affect water and energy consumption.

The results were compared with data comprised in studies by Kaleta and Wojdalski [2007] and Wojdalski and Dróżdź [2001, 2002]. It results from the quoted papers that factory per-manufactured-unit electrical energy consumption in dairy plants where milk in powder was not manufactured amounted to 39.5 – 39.9 kWh/1000 l, and in plants with a limited production profile (consumer milk and lactic fermentation beverages, i.e. similar to the plant under study) ranged from 30.7 – 32.1 kWh/1000 l.

According to WS Atkins Int. [1998] energy effectiveness (expressed by W_c coefficient), for dairy plants amounts on average to 2.01 GJ for each one thousand of litres of the processed milk. In the plant under study the coefficient numerical value is by ca 10% greater.

The factory per-manufactured-unit water consumption, in turn, was materially smaller from the data found in the literature since it represented 50 – 60 % of numerical values of those coefficients contained in the literature quoted.

The increased factory per-manufactured-unit electrical energy consumption may have been affected by an increased participation of refrigeration in the energy balance. The consumption of thermal energy depended on the season in which the plant was operating. Generally, an increased energy consumption resulted from partly unused manufacturing capacity of the plant which curtailed manufacturing eco-effectiveness in the plant under study. In turn, factory per-manufactured-unit water consumption could have been affected by the use of this energy carrier in a closed cycle.

Coefficients presented in Table 1 may be applied for the manufacturing plant environmental impact analysis.

As a result of converting coefficients W_{t1} and W_{t2}, while taking into account calorific values of different fuels contained in the literature on the subject [Niedziółka and Zuchniarz, 2006, Rosiński et al., 2006], Table 3 presents the consumption of the referred to energy carriers (real fuel). Calorific values Q_w^r expressed in GJ/kg of real fuel were used for these calculations.

Table 3. Consumption coefficients of factory per-manufactured-unit energy originating from different fuels

Energy Carriers	Calorific Value Q_w^r, [MJ/kg]	Coefficients of factory per-manufactured-unit energy consumption	
		W_{rz1} [kg/1000 litres of processed milk]	W_{rz2} [kg/1000 litres of processed milk]
Barley Straw	16.1	189.0	152.7
Brown Coal	14.0	217.3	175.6
Colza Straw	15.0	202.8	163.9
Fuel Oil	42.6	71.4	57.7
Hard Coal	26.0	117.0	94.6
Liquid Flammable	37.2	81.8	66.1
Maize Straw	16.8	181.1	146.4
Natural Gas	32.0	95.1	76.8
Pellets	18.0	169.0	136.6

Sawdust	19.3	157.6	127.4
Straw Briquettes	17.1	177.9	143.8
Vegetable Oil	37.5	81.1	65.6
Waste Engine Oil	41.5	73.3	59.3
Wheat Straw	17.3	175.9	142.1
Willow Chips	16.5	184.4	149.0
Wood Briquettes	18.0	169.0	136.6
Wood Powder	17.0	179.0	144.7

The selected numerical data comprised in Table 3 may be important when analyzing possibilities of substituting traditional fuels by energy originated ones from renewable sources. In specific cases transformation efficiency of a given energy carrier into thermal energy should be taken into consideration.

The results comprised in this paper may serve for comparison with those of other dairy processing plants [Marks and Gut, 2007, Peng et al., 2001, Prasad et al., 2002, Wojdalski and Dróżdż 2002, Özbaya and Demirer, 2007, Wendorff, 2007]; they also supplement the knowledge with regard to the application of energy from renewable sources in other branches of the food processing industry [Wojdalski et al., 2007].

SUMMARY AND CONCLUSIONS

In the plant under analysis values of energy consumption coefficients were increased as compared with those found in the literature quoted. It arose from making an incomplete use of its manufacturing capacity. At the same time factory per-manufactured-unit water consumption was substantially smaller than the results achieved in similar plants which proves high manufacturing eco-effectiveness reached when using that carrier. It is justified, then, to conduct active monitoring as one of the best techniques of energy economy management in conjunction with the current production volume. The presented results may serve to determine environmental standards or verification thereof as well as implementation of principles of cleaner manufacturing. Besides, coefficients comprised in this paper may serve to assess manufacturing costs, atmospheric pollutant emission costs and pollution load into waters

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