AIMS Geosciences, 6(4): 491–503.
DOI: 10.3934/geosci.2020027
Received: 03 September 2020
Accepted: 09 November 2020
Published: 17 November 2020

http://www.aimspress.com/journal/geosciences

Research article

Energy and water efficiency in the gelatine production plant

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Abstract: Nexus water-energy-food can be represented on a micro scale using the example of gelatine production in a rendering plant. The article presents the results of research on the variability of energy and water consumption in a rendering plant producing food gelatin. Monthly production was 565.2–631.3 Mg of gelatin and on average 18.89 Mg of gelatin was produced per day. The power of the installed electrical devices was 1150 kW. The average unit consumption of water was 18.97 m^3/Mg, heat energy 22.39 GJ/Mg and electricity 1174.76 kWh/Mg. The influence of gelatine production on energy and water consumption was determined. It has been shown that in the examined plant there is an increased by about 20–30% non-production consumption of energy and water, which in the future should be reduced by introducing technological innovations. Moreover, it has been shown that there is a possibility of increasing production efficiency. The obtained energy efficiency and unit consumption indicators can be used to define environmental standards as well as eco-efficiency and production costs important for management of the enterprise.

Keywords: rendering industry; food industry; production energy consumption; energy efficiency; water consumption; energy consumption; mechanical properties

Abbreviations: $e_{e\,CO2}$: CO_2 emissions per 1 kW·h of generated electrical energy (0.90–1.02 kg CO_2/kW·h); $e_{te\,CO2}$: CO_2 emissions associated with gas fuel combustion (55.82 kg/GJ); A_n: energy consumption; A_{te}: monthly consumption of thermal energy ($A_{te}= B_{rz}\,Q_w^r \cdot 10^{-6}$), GJ; A_e: monthly active electricity consumption, kW·h/month; A_{t1}: total energy consumption (including conversion factor 1 kW·h = 0.012 GJ), GJ; A_{t2}: total energy consumption (including conversion factor 1 kW·h = 0.0036 GJ), GJ; A_w: monthly water consumption, m^3; B_{rz}: monthly real fuel consumption (fuel gas), m^3; $E_{e\,CO2} = W_e \cdot e_{e\,CO2}$: Specific CO_2 emission associated with electricity generation in the plant kg CO_2/Mg of product; $E_{te\,CO2} = W_{te} \cdot e_{te\,CO2}$: Specific CO_2 emission associated with gas fuel combustion in the plant kg CO_2/Mg of product; EE_e: efficiency of electricity consumption, [kg of product/kW·h]; EE_{se}: efficiency of consumption of steam equivalent [kg of product/Mg]; EE_{te}: efficiency of thermal energy consumption [kg of product/GJ]; EW: water consumption efficiency [kg of product/m^3]; K: relations between production and the number of employees, [Mg gelatine/person]; K_1: cubature of production space of the plant for Mg of gelatine, [m^3/Mg]; K_m: installed capacity of electrical devices on Mg of produced gelatine per 24h, ($K_m = P \cdot Z_d^{-1}$) kW/Mg of product; P: installed capacity of electrical appliances, kW; r: correlation coefficient; R^2: coefficient of determination ($r^2 \cdot 100\%$); Q_{ce}: calorific value of fuel equivalent, 29.3076 MJ/kg c.e.; Q_n: energy streams; Q_{se}: energy value of water vapour (steam) equivalent, 2.6796 MJ/kg s.e.; Q_w^r : real fuel calorific value, MJ/m^3, GJ/m^3; W_{st}: specific steam consumption in the plant, GJ/Mg of product; W_{te}: specific heat consumption in the plant, GJ/Mg of product; W_e: specific electrical energy consumption in the plant, kW·h/Mg of product; W_{ce1}: specific consumption of equivalent fuel, taking into account the relation 1 kW·h = 0.012 GJ, kg c.e./Mg of product; W_{ce2}: specific equivalent fuel consumption, calculated based on 1 kW·h = 0.0036 GJ, kg c.e./Mg of product; W_{se}: specific steam equivalent consumption in the plant, kg/Mg of product; W_{rs}: specific actual steam consumption, kg/Mg of product; W_{r1}: overall specific energy consumption contained in real fuel (calculated based on 1 kW·h = 0.012 GJ), GJ/Mg of product; W_{r2}: overall specific energy consumption contained in real fuel (calculated based on 1 kW·h = 0.0036 GJ), GJ/Mg of product; W_{t1}: overall specific energy consumption (calculated based on 1 kW·h = 0.012 GJ), GJ/Mg of product; W_{t2}: overall specific energy consumption (calculated based on 1 kW·h = 0.0036 GJ), GJ/Mg of product; W_w: specific water consumption for the monthly period ($W_w = A_w \cdot Z^{-1}$), m^3/Mg of product; Z_m: monthly production of gelatine, Mg; Z_{24}: daily production of gelatine, Mg; η: energy transformation ratio; η_b: efficiency of the steam boiler

1. Introduction

The agri-food industry is highly dependent on the extraction of fossil fuels and contributes significantly to greenhouse gas emissions. The world population is also growing and the demand for food is expected to increase by 60% by 2050 [1] while at the same time water consumption will increase and the demand for energy (including electricity) [2]. For people managing the company, the effectiveness of the company's operation is an important issue. Efficiency can be considered, inter alia, as production efficiency or as energy efficiency. Production efficiency is defined as the result of economic (industrial) activity which is the quotient of the obtained effect to the expenditure. Energy efficiency is expressed analogously or can be defined as a reduction in energy consumption. The reduction in energy consumption takes place at the stage of production (transformation), transmission, distribution or end use, mainly as a result of changes in technology. The use of innovative technological solutions that provide the same or higher level of production or services [3] has a positive impact on the enterprise and its environment [2]. One of the possibilities of expressing energy efficiency is the energy consumption of production, i.e. energy demand to carry out a specific production process. It is closely related to eco-efficiency consisting in achieving high environmental results consisting in reducing the consumption of natural resources, reducing emissions of environmental pollutants and reducing the mass of generated waste [4,5]. Gelatin is an important biopolymer used in food to improve flexibility, consistency and structural stability. It can be obtained not only from the skin and bones of land animals, but also from fish and insects. Two methods are usually used in the production of gelatine: acidic and alkaline to obtain gelatin A type and B type respectively [6]. The raw materials for the production of gelatine are post-production waste from the food industry in the meat, poultry and fish industries. Pork gelatins are the most popular and widely used, but they are subject to severe limitations and skepticism among consumers due to socio-cultural and health problems [7]. Gelatin and gelling agents improve the quality and shelf life of stored food products [8,9]. Gelatin-based products can be used as foils for packing various products to reduce the negative impact on the environment [10,11]. Issues related to the production of gelatine (health, cultural, religious issues) based on various raw materials (mammals, fish, poultry, insects) and the possibility of its wide use in the economy are issues that constitute a research area in many academic centers [12–14]. An example of obtaining gelatine from tuna skin on a laboratory and industrial scale is presented in the work of Montero [15]. Meyer presented the processing of collagen-based biomaterials and the properties of the obtained materials [16].

The consumption of energy carriers in rendering plants depends on many factors, the most common of which are the physical and chemical properties of the processed raw material, production technology [12,17,18]. The literature also mentions numerous applications of gelatin in the food, pharmaceutical and electronic industries [7,19,20]. The purified and demineralized gelatin solution consists of more than 95% water. As a rule, concentration takes place in a multi-stage vacuum system with the use of plate, circulation or thin-film evaporators. Dried gelatine has a residual water content of 10–12% and has a long shelf life from a microbiological point of view [21]. The strong influence of pre-treatment and extraction conditions on the yield and properties of fish gelatine need to be taken into consideration in an industrial setting, and usually a compromise between yield, desired properties, and energy efficiency needs to be considered for optimal production [22]. The set of requirements and principles aimed at effective environmental protection in accordance with the requirements of the best available production technique is included in the document [23]. Although the discussed issues are devoted to sample publications [21,24–26], many issues related to the production process in the plant in operational terms have not been fully explained. Therefore, it is new to explain the reasons for the variability in the consumption of energy and water, especially the impact of the production volume, the degree of mechanization of production operations and the degree of capacity utilization on energy and water consumption. The aim of the study was to determine the efficiency of energy and water management in a gelatine production plant. The literature review shows that so far no studies have been carried out on energy and water consumption, taking into account the general characteristics of the production plant. In addition, the work was to provide materials helpful for the construction of models of plants in this industry as energy users and the search for the relationship between the adopted independent variable—the amount of gelatine production and the demand for energy carriers that may be one of the elements of the analysis of production efficiency. It is also an innovation compared to the method presented in [27].

2. Materials and methods

Research materials were collected in 2019 at a rendering plant that produces pork gelatin for food and pharmaceutical purposes. Direct measurements of energy and water consumption were carried out and the production volume was obtained from the plant's accounts. The plant employs 144 people, including 120 production workers. The total area of the enterprise is 53,000 m^2. The cubature of all working space is 32,350 m^3, including production space—21,456 m^3. The monthly production volume of Z_m gelatine was within the range of 565.2–631.3 Mg, the average daily Z_d is about 18.5 Mg. The total installed electric power of rendering plant P was 1150 kW.

Figure 1 shows the levels of energy transformation in the plant. The scope of the research carried out covered the total consumption of energy and water at level I. Level II covers the transformation of energy carriers. On level III, there are energy and water receivers in the waste processing line for meat production and gelatine production.

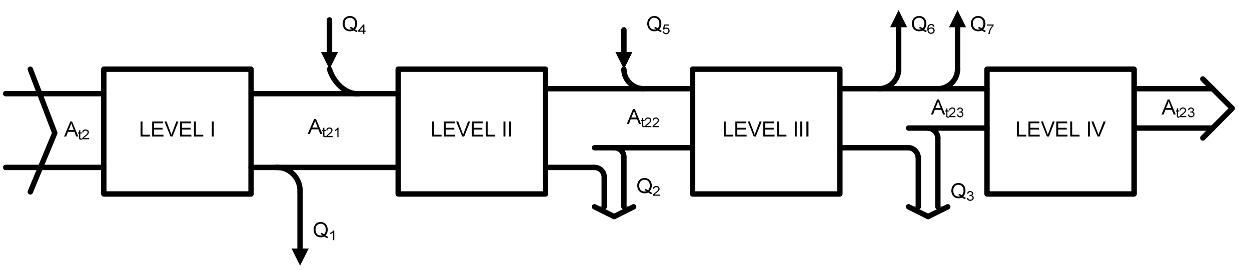

Figure 1. Stages (levels) of transformation of energy carriers. Source: own elaboration.

Figure 2 shows the most important processes that are implemented at level III, which make up the gelatine production technology in the examined plant. From the point of view of energy consumption and energy efficiency of production, the aim should be to maximize the value of A_{t23} (at level IV, Figure 1) as the so-called energy input, i.e. simultaneously strive to increase the total energy transformation coefficient $\eta_{III} = A_{t23}/A_{t2}$.

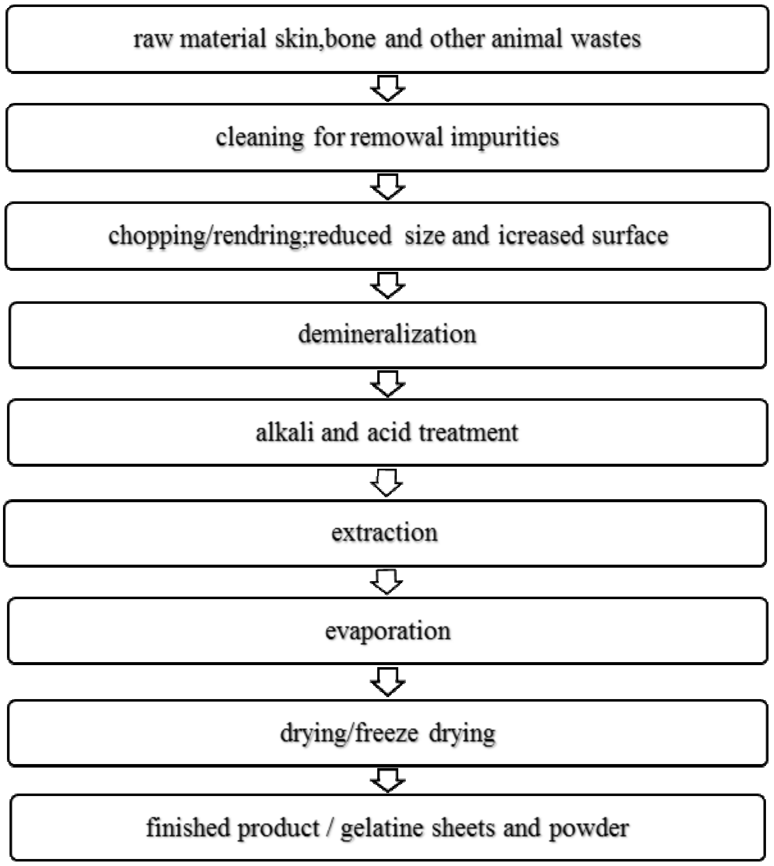

Figure 2. A simplified technological scheme for the production of gelatine. Source: own elaboration.

Previous studies most often present the consumption of heat or electricity separately at level III [22,28,29]. It should be noted that from the point of view of costs and the choice of a specific technology, it is important to use the cumulative energy consumption of a product or an indicator that would include the total energy consumption both in the production plant (A_{t2}) as well as converted to primary energy (A_{t1}). For this purpose, the following indicators of specific energy consumption were adopted:

$$W_{t1} = \frac{A_{t1}}{Z} = \frac{0{,}012 \cdot A_e + B_{rz} \cdot Q_w^r \cdot 10^{-6}}{Z} \quad \text{GJ/Mg of gelatine} \tag{1}$$

$$W_{t2} = \frac{A_{t2}}{Z} = \frac{0{,}0036 \cdot A_e + B_{rz} \cdot Q_w^r \cdot 10^{-6}}{Z} \quad \text{GJ/Mg of gelatine} \tag{2}$$

In the formula above, A_{t2} is the total energy consumption entered into level I.

The above energy consumption rates were converted into fuel equivalent (W_{ce}) or water vapor (steam) equivalent (W_{se}) rates using the following formulas:

$$W_{ce1} = W_{t1}/Q_{ce} = 3412.08 \cdot 10^{-2} W_{t1} \tag{3}$$

$$W_{ce2} = W_{t2}/Q_{ce} = 3412.08 \cdot 10^{-2} W_{t2} \tag{4}$$

$$W_{se} = W_{te}/Q_{se} = 373.19 \cdot Q_{se} \cdot W_{te} \tag{5}$$

At the same time, the W_{ce1} and W_{ce2} indices were converted into energy that can be obtained, for example, from renewable sources, using the following formulas expressing the specific actual fuel consumption rates W_{r1} and W_{r2}.

$$W_{r1} = W_{t1}/Q_w^r \quad (6)$$

$$W_{r2} = W_{t2}/Q_w^r \quad (7)$$

The inverse of the energy and water consumption indicators are the corresponding energy and water consumption efficiency indicators.

It was assumed that the production volume (Z) influences the consumption of energy carriers in a production plant. This factor was adopted due to the greatest suitability for the assessment of the environmental impact of plants in this industry and determination of the best available production techniques [25,30].

In order to explain the dependence of energy carrier consumption (A) on the independent variable (Z)—which is the actual value observed in practice, the following equation was adopted:

$$A = b + aZ \quad (8)$$

in which: A—consumption of energy carriers (dependent variable—A_e, A_c, A_w, W_e, W_c, W_w), Z—production volume (independent variables; Z_m or Z_{24}).

Under the conditions:

$$aZ \geq b \text{ and } Z \geq 0 \quad (9)$$

The application of the obtained regression equations [31] taking into account the correlation and determination coefficients (r and R^2) allows to partially explain the discussed problem in the analyzed gelatine production plant.

3. Results and discussion

The Table 1 presents the ranges of technical and organizational indicators characterizing the tested plant. The K_m, K_1 and K indices express the relationship between the technical equipment and the production volume as well as the number of employees in the production departments of the plant. The K index can also be partially used to evaluate the production efficiency of an entire production plant.

Table 1. Technical and organizational indicators of the examined plant for daily periods. Source: own elaboration.

Lp	Indicator	Unites of measure	Range	
			Minimum	Maximum
1	K	Mg gelatine/person	0.156	0.175
2	K_1	m^{3}production space/Mg gelatine	1.132	1.265
3	K_m	kW/Mg gelatine	52.5	68.0

In order to achieve the aim of the study, a model of the agri-food industry plant as a user of energy carriers was used, as well as company indices of unit consumption of energy and water carriers defined in the methodology presented in publications on other sectors of the agri-food industry [32,33]. The average value of the K_m index for the daily period was 62.2 kW/Mg.

The obtained research results refer to the production conditions specified in Table 1 and may be important for industrial practice. Technological innovations implemented in the enterprise reduce energy and water consumption at level III (Figure 1). The energy intensity of production and water consumption indicators included in the paper are factors used to assess the functioning of the whole production plant covering level I (Figure 1). These indicators include the consumption of energy carriers for production and non-production purposes, losses and operating conditions. It is an innovative approach in relation to previous studies, as it covers not only the production process, but the entire operation of the plant.

Table 2 shows the ranges of variability in the consumption of energy carriers during the annual period.

Table 2. Consumption of energy carriers and water as well as selected environmental indicators.

Dependent variable, indicators		Range	Medium
Electricity	W_e [kW·h/Mg gelatine]	1154.9–1202.7	1174.8
	EE [kg gelatine/kW·h]	0.831–0.866	0.851
Thermal energy	W_{te} [GJ/Mg gelatine]	20.16–24.66	22.39
	EE_{te} [kg gelatine /GJ]	40.55–49.60	44.66
Equivalent water vapour	W_{se} [kg vapour/Mg gelatine]	7523–9202	8355
	EE_{se} [kg gelatine/Mg vapour]	108.7–132.9	119.7
Total energy	W_{t1} [GJ/Mg gelatine]	34.02–39.09	36.49
	W_{t2} [GJ/Mg gelatine]	24.32–28.99	26.62
Fuel equivalent	W_{ce1} [kg/Mg gelatine]	1160.8–1333.8	1245.0
	W_{ce2} [kg/Mg gelatine]	829.8–989.1	908.3
CO_2 emissions	$E_{e\,CO2}$ [kg CO_2/Mg of gelatin]	1107–1154	1127
	$E_{te\,CO2}$ [kg CO_2/Mg of gelatin]	1065–1303	1183
Water	W_w [m^3/Mg of gelatine]	10.23–25.84	18.97
	EW [kg gelatine/m^3]	38.7–97.8	52.7

The average unit electricity consumption W_e (Table 2) in particular months showed seasonal fluctuations amounting to over 4%. Unit heat energy consumption W_{te} in extreme cases differed from each other by approx. 22%. Unit water consumption showed the greatest differentiation (approx. 2.5

times). Assuming daily or monthly periods, regression equations were obtained expressing the variability of energy and water consumption presented in Table 3. Only equations for which regression was significant were taken into account.

Table 3. Effect of gelatine production on the consumption of energy carriers. Source: own elaboration.

Regression equation	The range of variability of production Z	Correlation coefficient r	Coefficient $R^2 = r^2 \cdot 100\%$
$A_e = 1424.4\ Z_m - 147450$	565.2–631.3	0.878	77.3
$A_c = 21.986Z_{24} + 7.6436$	16.9–21.9	0.791	62.6
$A_w = 95.655Z_{24} - 1439.1$	16.9–21.9	0.883	77.9
$W_w = 3.8879\ Z_{24} - 54.464$	16.9–21.9	0.818	67.0
$EW = -13.561Z_{24} + 320.74$	16.9–21.9	0.612	37.42

The production volume Z_m in approximately 77.3% influenced the consumption of electric energy Ae, and the consumption of heat energy in 62.6%. It was also shown that the variability of water consumption was in 77.9% conditioned by the volume of gelatine production.

The obtained results were compared with the data contained in the work [21] in which the consumption of energy carriers for gelatine production with the use of various technologies was investigated. As a result of the conducted research, it was observed that depending on the technology used, different amounts of energy and water are required. The lowest consumption was in the production of pork gelatine using the acid method. The production of 1 kg of gelatine required the supply of 20–25 kg of steam, 3–5 kW·h of electricity and approximately 150 dm^3 of water. In the case of the alkaline technology with the use of animal skin, the water requirement increased to approximately 400 dm^3/kg of gelatine. According to [17,18], the energy consumption of the production of rendering plants (expressed by the W_e index) is on average 100–2000 kW·h /Mg of raw material. Water vapour (steam) consumption is W_{rs} = 0.9–1.3 Mg/Mg of raw material (with the efficiency of a steam boiler η = 0.5–0.6, located at level II). The unit water consumption rate W_w was 7–65 m^3/Mg of the final product. The conducted research shows that the unit consumption of electricity and real steam was significantly lower than the data in the literature, as it accounted for 50–60% of the numerical values of these indicators included in the quoted literature. Water consumption per product unit was within the limits for these indicators mentioned in the cited literature. The reduced unit energy consumption could have been influenced by the increased technological progress and the application of energy-saving production technology and apparatus at levels II and III. Generally speaking, the reduced energy consumption resulted from the increased utilization of the processing capacity, which at the same time increased the production efficiency in the examined plant. The energy consumption was also conditioned by the seasonality of the plant's operation. The correlation coefficients "r" listed in Table 3 prove the existence of secondary (side), non-production energy consumption Q_1–Q_3, Q_6 and Q_7. Streams Q_4 and Q_5 represent energy recovery.

Referring also to the works [23,26], the results of the presented research, partially answer the question of how to optimize the efficiency of gelatine production in terms of energy and water consumption. The efficiency of thermal energy consumption (EE_{te}) in individual months differed by 22.3%. There was no significant correlation between the volume of gelatin production and the EE_{te}

index. The observations of the production course also lead to the conclusion that reducing the energy consumption of the compaction process and other thermal treatment processes (at level III, Figure 1), may reduce Q_3 losses and increase the efficiency of energy transformation $\eta_{III} = A_{t23}/A_{t22}$ at the same time. As a result, the coefficient η and the efficiency of heat energy consumption EE_{te} will also increase.

In turn, the specific water consumption of W_w could have been influenced by the use of closed circuits. The indicators presented in Table 2 may be used in the analysis of a production plant's environmental impact.

As a result of the conversion of the W_{t1} and W_{t2} indices, taking into account the calorific values of various fuels contained in the literature [34], Table 4 shows the consumption of the above-mentioned energy carriers (real fuel). Calorific value Q_w^r expressed in GJ/kg of real fuel was used for the calculations.

Table 4. Indicators of unit energy consumption from various fuels.

Energy carriers	Calorific value Q_w^r, [MJ/kg]	Individual fuel consumption indicators	
		W_{r1} [kg/Mg gelatine]	W_{r2} [kg/Mg gelatine]
Lignite	14.0	2606.4	1901.4
Coal	26.0	1403.5	1023.8
Natural gas	32.0	1140.3	831.9
Heating oil	42.6	856.6	624.9
Vegetable oil	37.5	973.1	65.6
Liquid flammable waste	37.2	980.9	715.6
Wheat straw	17.3	2109.2	1538.7
Barley straw	16.1	2266.4	1653.4
Corn straw	16.8	2172.0	1584.5
Rapeseed straw	15.0	2432.7	1774.7
Wood dust	17.0	2146.5	1565.9
Scobs	19.3	1890.7	1379.3
Willow chips	16.5	2211.5	1613.3
Pelets	18.0	2027.2	1478.9
Straw briquettes	17.1	2133.9	1556.7
Wood briquettes	18.0	2027.2	1478.9

From the point of view of energy production from fossil fuels and next reducing energy consumption, it is very important to use alternative fuels properly. Selected figures included in Table 4 may be important when analyzing the possibility of replacing traditional fuels with energy from renewable sources. In individual cases, the efficiency of transformation of a given carrier into thermal energy should be taken into account, especially at level II. The results contained in the study can be used for comparison with other plants in the gelatine production industry [7,8,35–41] as well as supplement the knowledge on the use of energy from renewable sources in other sectors of the food industry [30,32,33,42–44]. The nexus of energy and water consumption in industrial production is an important issue in the sustainable development of the economy [45] and the nexus between water-energy-food is being used to indicate the importance of managing them together [46].

4. Conclusions

In the analyzed plant, the energy consumption indicators had lower values as compared to the cited literature (lower even 50–60%). This was due to the increased use of the existing processing capacity. These results showed that it is possible to reduce energy consumption through better management of the technological process. The obtained results allow for the conclusion that it is possible to reduce the negative impact on the environment (lower energy demand, more effective water management) and to reduce the plant operating costs. Moreover, these results lead to the conclusion that after the implementation of technological innovations, it will be possible to further reduce energy consumption. As we can observe, the technical aspects are important as well as economic and ecological aspects. At management techniques in combination with the current production volume.

The presented results can be used to define environmental standards or their verification as well as to implement the principles of cleaner production as they relate to the existing organizational and production conditions as well as the degree of use of the installed power of electrical devices. It has been demonstrated and justified that on the micro-scale it is possible to introduce the nexus water-energy-food. Moreover, the indicators included in the work can be used to estimate the production costs and the emission of pollutants into the atmosphere and the pollutant load into the waters. In the same time, the unit water consumption proves the high eco-efficiency of using this medium. Therefore, as recommendation for company managers, justifies active monitoring as one of the best energy.

In the future, further research could be focused on reducing energy consumption in the evaporation and drying process at the level III, as these are high-energy processes. In addition, it is worth exploring the possibilities of energy recovery from processes at the level II. It also will be important to pay attention to the overall reduction of water consumption in the enterprise.

Conflict of interest

All authors declare no conflicts of interest in this paper.

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