RECTIFIED ETHANOL PRODUCTION COST ANALYSIS

by

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This paper deals with the impact of the most important factors of the total production costs in bioethanol production. The most influential factors are: total investment costs, price of raw materials (price of biomass, enzymes, yeast), and energy costs. Taking into account these factors, a procedure for estimation total production costs was establish. In order to gain insight into the relationship of production and selling price of bioethanol, price of bioethanol for some countries of the European Union and the United States are given.

Key words: *bioethanol, investment costs, operating costs, total production costs*

Introduction

Ethanol is a compound that has found applications in many fields of human activity: in medicine as an antiseptic, in chemical industry as a solvent and for the synthesis of organic compounds, in the alcoholic beverages industry,… In the past few decades more and more ethanol is used as a fuel or fuel additive. The importance of fuel ethanol the best illustrated by the fact that in the period from 1979 to 2003 year production of ethanol in the U. S. has increased 280 times [1]. Also, world ethanol production for transport fuel tripled in the period from 2000 and 2007 year. Ethanol is most commonly used to power automobiles, though it may be used to power other vehicles, such as farm tractors, boats, and even airplanes. Because of that, ethanol has strategic value because it is a renewable energy source and reduces the dependence on foreign oil imports.

This paper refers to the analysis of production costs of rectified ethanol (96.2 vol.%) by conventional methods from grains and takes into consideration local (Serbian) market conditions from 2009. Rectified ethanol also can be used as a fuel, but it is necessary to remove water from it. Production of pure ethanol (99.9 vol.%) with no water from rectified ethanol require further purification. For the production of pure ethanol some of these procedures can be used: permeation, pervaporation, azeotropic distillation, and adsorption.

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Methodology applied in this research can be used for analysis of economic efficiency of ethanol production in various market conditions. It is shown that ethanol production costs depend greatly on heat consumption, fuel price and feed price. In addition, this paper contains a brief overview of current state in the area of ethanol production in the developed countries.

Investment cost

As far as ethanol production plants are concerned, the overall investment costs depend on the variety of different factors. Main are the type of the feed used in the process, plant capacity and final product quality.

Types of carbohydrates which are contained in the feed (sugars, starch or lignocelluloses) affect the final price of ethanol. This is because they determine the applied technological procedure, which, in term, defines the investment costs. Lignocellulos feeds require much greater investment costs compared to starch or sugar feed [2].

If construction of new plants for ethanol production from corn in USA is observed, it can be shown that the average investment costs in 2008 reduced to the annual plant capacity in liters of absolute alcohol (lAA) are 0.44 €/(lAA/year) [2]. More than 60% of the overall investment value is used for the basic equipment (columns, reservoirs, heat exchangers, *etc*.), piping, fittings, *etc*. On the other hand, investment costs for plants that use lignocellulos feed are significantly greater and in 2009 were about 0.94 €/(lAA/year) [2].

However, if second-hand equipment is used for construction of ethanol plant, investment costs are significantly reduced, and can be lower than 0.26 €/(lAA/year) [3].

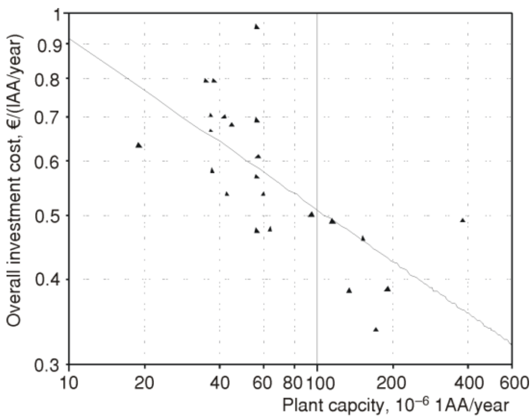

Figure 1. Correlation between plant capacity and overall investment costs

Naturally, the higher the plant capacity is the higher the investment costs are. However, if investment costs are reduced to the unit of product per year, *i. e*. €/(lAA/year), it can be shown that when greater capacity plants are concerned the investment costs have only minor influence on the overall production costs, and thus on the final product price. This correlation between investment and capacity of plants built in USA presented in fig. 1, are given in [4], based on 2010 costs.

Investment cost can be estimated by parametric method using the equation:

$$\frac{C_2}{C_1} = \left(\frac{S_2}{S_1}\right)^n \tag{1}$$

where C_2 is the investment cost of the new plant with the capacity S_2, C_1 – the investment cost of the existing plant with the capacity S_1.

Statistical analysis of the data in [4] yields the exponent of n = 0.75 (mean square deviation is 16,7%). This value corresponds well to the value of n = 0.73 given in [5].

Operating cost

Operating costs (C_{ope}) include costs of working matters, energy, labor, and other costs.

Acquisition of raw materials

Variable costs depend mostly on the acquisition of raw materials. This cost makes up approximately 50-70% of the overall operating costs of the plant [3, 6]. When considering the feed fitness for the process, its price has to be taken into consideration along with its ethanol yield per mass unit of the feed. The average ethanol yields of the most commonly used cultures, as well as the quantities of ethanol which can be obtained from them are shown in tab. 1.

Table 1. Average ethanol yield based on the feed used [7-9]

Feed	Wheat	Corn	Sugar beet	Sugar cane
Culture yield reduced to the unit of agricultural area, [tha^{-1}]	3.5	7	66	100
Ethanol production reduced to the ton of the feed, [lt^{-1}]	370	350	95	65
Ethanol production reduced to the unit of agricultural area, [lha^{-1}]	1295	2450	6270	6500

Feed prices, as well as its yield depend mostly on the climate conditions [10]. Therefore, in tropical countries (such as Brazil) ethanol production is based on sugar cane, while in moderate climate countries (Europe, USA) ethanol production is based on corn. Influence of the type of feed on the overall ethanol production costs according to the data from 2003 is shown in tab. 2.

Table 2. Influence of the feed type on the overall ethanol production costs [11-14]

Feed type	Country	Overall production costs [€/lAA]
Sugar cane	Brazil	0.23-0.28
Starch and sugar feed	Europe and USA	0.38-0.54
Lignocellulose feed	USA	0.73-0.80
	Europe	0.81-1.07

According to the data from 2009, corn price in Serbia was 120 €/t (this price does not include value added tax – VAT) [15], although in the period just after the harvest corn can be bought for significantly lower price of 80 €/t. Corn price in the world market has similar value, and for example, according to [16] in December of 2009 it was 137.5 €/t.

Transport costs can have a significant influence on the feed price, depending mainly on the length of the transport. According to [6] and [10] feed transport and storing costs usually make up to 10% of the overall production costs.

The other raw materials used in the process (mainly enzymes and yeasts) are much cheaper and require much less assets. According to [17] their share in the overall production costs is 1.3%, while in [18] it is stated that for the plant of the capacity of $150.9 \cdot 10^6$ lAA/year enzyme costs are 4,8% and yeast costs are 1.1%. Unit feed prices are shown in tab. 3.

Table 3. Unit feed prices according to [15] and [17]

Feed	Corn	Enzymes	Yeasts	Denaturation additives
Unit price	0.12 €/t	5 €/kg	0.516 €/kg	0.265 €/l

Energy-generating product costs

Energy costs present another significant item, and combined with raw material acquisition make up about 85% of the operating costs [17]. This datum is also confirmed by the analysis of the$180 \cdot 10^6$ l/year capacity plant, in which energy costs are 18% and raw material acquisition costs are 66% of the overall production costs [19].

Out of all energy costs, 75% are related to steam production. This steam is used for cooking, distillation, and rectification. The other 25% of the energy costs are related to electric energy consumption, process and cooling water, *etc*. [19, 20]. For plants that produce ethanol using the wet milling process [1], steam consumption is about 65% and electric energy consumption is about 30% of the overall energy costs [20].

According to [21] natural gas price in Serbia is 0.417 €/m^3 (the calorific value 33338 kJ/m^3), while heavy fuel oil price is 390.5 €/t (the calorific value 40000 kJ/kg). If boiler efficiency of 90% is assumed, steam price is 32.83 €/t if produced by using natural gas, that is 24.46 €/t if steam is produced by using heavy fuel oil. Here it has to be stressed that energy-generating product prices vary significantly in other countries. So, according to [22] natural gas price in USA is 0.289 €/m^3, while according to [17], natural gas price in Italy is 0.268 €/ kg , that is 0.191 €/m^3.

Energy-generating product unit prices according to [17, 21, 23] are shown in tab. 4.

Table 4. Energy-generating product unit prices

Item	Water steam	Electric energy	Process water
Unit price	32.83 €/t – fuel: natural gas 24.46 €/t – fuel: heavy fuel oil	0.05 €/kWh	0.041 €/m^3

Byproduct production

It is possible to boost plant economic performance by selling distillery byproducts. It is stated in [18] that savings of up to 22.1% can be made in this fashion.

If ethanol is gained using a dry milling process it is possible that the waste from the process (which contains about 30-50% of dry matter) is used as wet cattle food, which can be used as feed to produce dry cattle food (DDGS – distillers dried grains with solubles) with dry matter content of 90% [24]. By processing 100 kg of corn feed about 33 kg of dry cattle food is gained [25]. However, drying the waste from ethanol production requires vast quantities of heat (up to 35% of the overall energy used [24]) which significantly augments total production costs. Nevertheless, cattle food price provides profitability to this procedure.

The other byproduct which can be sold is CO_2 which is created is large quantities during the fermentation process. However, only a small number of plants go to the extent of processing and selling this byproduct, as it is only profitable for large processing capacities. In addition, it is important that the CO_2 customer is located in the vicinity of the ethanol production plant in order to minimize transport costs [17].

Table 5 shows production costs, as well as the influence of byproduct prices on the reduction of the total production costs [8].

Table 5. Production costs (in €/lAA)

Feed	Overall production costs		Process byproduct price	Overall ethanol production costs
	Feed price	Other production costs		
Wheat	0.220-0.343	0.284	0.145	0.359-0.482
Sugar cane	0.200-0.324	0.218	0.003	0.415-0.539
Straw	0.240	0.355	0.038	0.557

It is not stated in the observed literature if the ethanol mentioned in this table is rectified or dehydrated. Ethanol dehydration process requires additional expenses for azeotropic distillation. According to [26], these costs are 0.0293-0.0421 €/lAA.

Other costs

Maintenance costs include labor and material costs (including spare parts). Their assessment is made based on information for maintenance costs of similar plants [23], or are assumed to be 3% of the overall investment costs [6, 17, 18].

Based on [17], administration expenses are 2% of the overall plant income.

Structure of the overall production costs for ethanol fuel production in the plant that uses dry milling process and has the capacity of $151 \cdot 10^6$ 1AA/year is shown in tab. 6 [18].

Table 6. Overall production costs structure

Item	Share [%]
Corn (feed)	58.48
Denaturation agents	1.96
Enzymes	3.80
Yeasts	0.90
Other raw materials	0.93
Energy costs	17.6
Cooling water	1.74
Labor	1.95
Maintenance	2.48
Insurance and administration	1.36
Amortization	8.79
Total	100

Ethanol selling price

Ethanol selling price includes producer's profit. Table 7 shows ethanol selling prices in Europe and USA according to [27], while the price in Serbian market is obtained from the rectified alcohol manufacturer.

Table 7. Ethanol selling price for ethanol purity of 96 vol.% and 99 vol.% in €/lAA

Country	Price 2009		Price 2008	
	96 vol.%	99 vol.%	96 vol.%	99 vol.%
Great Britain	0.65-0.67	0.64-0.69	0.62-0.70	0.75-0.81
Germany	0.64-0.66	0.65-0.71	0.67-0.69	0.74-0.81
France	0.63-0.67	0.64-0.70	0.66-0.69	0.72-075
Italy	0.63-0.66	0.65-0.68	0.67-0.69	0.74-0.78
USA	0.56-0.60	0.59-0.61	0.65-0.68	0.70
Serbia	0.83-1.04	–	–	–

Rectified ethanol production price in a distillery which has the capacity of 4000 lAA/day

This analysis is based on the production plant which uses the dry milling process for the production of rectified ethanol and uses corn as feed. Plant capacity is 4000 lAA/day, and the distillery works 330 days per year (7920 working hours). Distillery includes the following production units:

- plant for corn storing and grinding and corn stew brewing,
- saccharification plant,
- fermentation plant,
- continuous distillation plant for crude ethanol production,
- batch rectification plant for rectified ethanol production, and
- boiler plant with water treatment (uses heavy fuel oil).

Basic energy fluids in the distillery are water and steam.

Production of crude ethanol is done in the trayed column with reflux ratio of $R = 3.5$. Batch rectification is done by using the maximal (constant) amount of steam in the evaporator, while the reflux ratio controls the distillate flow. There are several fractions of distillate and the amount of first fractions is smaller than the main final product – main distillate. Therefore, it is not necessary to produce the same amount of ethanol-water vapor during the whole process.

One of the goals of the analysis of the reduction of utilities (steam and cooling water) by using two procedures:

- reflux ratio reduction to $R = 3$ while keeping crude ethanol quality, and
- modification of working regimes of rectification column and accompanying heat exchangers (evaporator and condenser) by reducing evaporator heat load while separating first fractions.

Overall production costs specification

When considering ethanol production economic efficiency, the overall year expenses include investment and operating costs [28]:

$$C_{\mathrm{tot}} = aC_{\mathrm{inv}} + C_{\mathrm{ope}} \tag{2}$$

where: a, [year^{-1}] is the amortization rate, C_{inv} – the overall investment costs, and C_{ope} – the operating costs.

For construction of the plant in question, the investor used mostly second hand equipment. Therefore, it is assessed that the overall investment costs reduced to the annual plant capacity are C_{inv} = 0,17 €/1AA. Amortizaton rate is calculated using $a = 1/10$ per year.

According to [29] for production of 4000 1AA/day it is necessary to use:

- 1145 kg per day of ground corn, that is 2.86 kg/1AA,
- 4 kg per day of alpha-amylase, that is $1\cdot10^{-3}$ kg/1AA, and
- 11.45 kg per day of glucoamylase, that is $2.86\cdot10^{-3}$ kg/1AA.

Distillery uses $3.04\cdot10^{-3}$ kg/1AA of baking yeast for fermentation. If the fermentation process was to use dry yeast the specific consumption would be $1.52\cdot10^{-3}$ kg/1AA.

Feed cooking process requires 395 kg of steam at low pressure of 4 bar (weight of one batch is 6500 kg, of which 1390 kg is corn) [29]. If the amount of steam is reduced to 1 lAA obtained from this feed (493 lAA) it results in steam consumption of 0.801 kg/lAA.

Steam consumption on daily level in the continuous distillation process (with reflux ratio of R = 3.5) is 12960 kg per day (0.15 kg/s [29]), and accordingly steam consumption reduced to 1 lAA is 3.24 kg/lAA. It is shown that reflux ratio can be reduced to R = 3.0 without any significant influence on the crude alcohol quality, which is later treated in batch rectification process. When reflux ratio in reduced to R = 3.0, steam consumption is also reduced and is 11520 kg per day, that is 2.88 kg/lAA.

According to [29], steam consumption in batch rectification process is 9370 kg per day, that is 2.4 kg/lAA. When the plant works with the optimized rectification regime, steam consumption is reduced to 1.94 kg/lAA.

For determining the average steam consumption two types of steam are taken into consideration. Firstly, steam used for separating first fractions (DPIII, DPII) and secondly, steam used for separating first grade distillate (DI).

The average steam consumption for production of 4000 1AA/day is 509 m^3/day [29], where water consumption is divided as follows:

– cooling during saccharification 203 m^3/day (39.9% water),
– fermenter cooling 51.6 m^3/day (10.1%),
– continuous distillation condensation and cooling 106 m^3/day (20.8%), and
– batch rectification condensation and cooling 148 m^3/day (29.1%).

Water consumption for cooking ground corn and mixing with crude alcohol in rectification are omitted from this list of items. This is because for these needs the heated water from the condenser, which has already been taken into consideration, is used.

Specific water consumption for the needs of condensation and cooling in batch rectification process is:

– 0.036 m^3/1AA, for regular rectification process, and
– 0.030 m^3/1AA, for optimized rectification process.

Electric energy consumers in the distillery are: screw conveyors for corn transport from silos to mill, mill for corn grinding, pumps, as well as other consumers (*i. e.* lighting, electrical appliances, *etc.*). Power of these electric energy consumers for the entire plant is 99 kW, and daily electric energy consumption is 2376 kWh. Electric energy prices only slightly differ on the domestic and international market. Therefore, the price of 0,05 €/kWh is taken as authoritative.

If plant maintenance costs are considered to be 3% of the overall investment costs, on the annual level it is necessary to set aside about 7500 € for maintenance. Reduced to 1 lAA this figure is 0.0051 €/lAA.

Tables 8 and 9 show how the listed factors influence the overall production costs.

Table 8. Production costs structure (feed preparation, electric energy and plant maintenance)

Item	Unit price	Specific consumption	Price [€/lAA]
Corn consumption	0.12 €/kg	2.86 kg/1AA	0.3400
Alpha-amylase consumption	5 €/kg	$1\cdot10^{-3}$ kg/1AA	0.0050
Glucoamylase consumption	3.5 €/kg	$2.86\cdot10^{-3}$ kg/1AA	0.0100
Baking yeast consumption	0.516 €/kg	$3.04\cdot10^{-3}$ kg/1AA	0.0020
Feed cooking steam consumption	24.46 €/t	0.891 kg/1AA	0.0196
Water consumption – saccharificator cooling	0.041 €/m^3	$50.75\cdot10^{-3}$ m^3/1AA	0.0021
Water consumption – fermenter cooling	0.041 €/m^3	$12.90\cdot10^{-3}$ m^3/1AA	0.0005
Electric appliances	0.05 €/kWh	0.594 kWh/1AA	0.0297
Plant maintenance	–	–	0.0051
Total			0.4140

Table 9. Production costs structure for distillation and rectification

Operation	Fluid	Unit price	Conventional procedure		Optimized procedure	
			Specific consumption	Price [€/1AA]	Specific consumption	Price [€/1AA]
Continuous distillation	Steam	24.46 €/t	3.24 kg/1AA	0.0793	2.88 kg/1AA	0.0704
	Water	0.041 €/m^3	0.002655 m^3/1AA	0.0011	0.002355 m^3/1AA	0.0010
Batch rectification	Steam	24.46 €/t	2.35 kg/1AA	0.0575	1.94 kg/1AA	0.0475
	Water	0.041 €/m^3	0.003700 m^3/1AA	0.0015	0.003000m^3/1AA	0.0015
			Total	0.1394		0.1204

Analysis of savings gained in processes of continuous distillation and batch rectification

Saving of 11.2% is obtained by reducing reflux ratio in the feed column. If observed on the annual level this saving is 11900 €/year. If energy fluids are taken onto consideration savings are:

- in steam 475.2 t/year (25.3 t/year of heavy fuel oil), and
- in process water 396 m^3/year.

By using batch rectification with optimized working regime, savings of up to 16.9% are made. On an annual level this figure is 13200 €/year. These savings include:

- steam savings of 541.2 t/year (which coincides with heavy fuel oil savings of 28.8 t per year), and
- process water savings of 924 m^3/year.

Analysis of economic profitability of stripping

Production costs presented so far refer to the costs of ethanol production until the end of separation of the first grade distillate. After this phase of the process is finished, the final fractions are separated. At the beginning of separation of these final fractions, ethanol fraction in the distillate cannot be disregarded, and therefore its separation from these fractions is economically profitable. It is for this reason that the final fractions are separated and again treated in the process of batch rectification. As time passes, the amount of ethanol gained (lAA/h) is reduced and because of this the overall production costs reduced to the product unit (€/lAA) are constantly increasing. Baring this in mind, it is necessary to determine the moment after which it is not economically profitable to continue stripping the feed.

Main costs which determine the overall production costs in this case are the costs of steam and cooling water. Analysis of economic profitability of stripping will be determined by:

$$C_{EP} > PC_p + WC_W \tag{3}$$

where C_{EP} [€/1AA] is the ethanol selling price, P [kg/1AA] – the steam consumption, C_P [€/kg] – the steam price, W [t/1AA] – the water consumption for condensation and cooling in the process of batch rectification, and C_W [€/m^3] – the water price.

Further analysis refers to the previously mentioned prices which are applicable in Serbia C_{EP} = 0.39 €/1AA, C_P = 0.02446 €/kg, and C_W = 0,041 €/m^3.

Steam consumption (P) consists of steam consumption in the process of stripping the feed and steam consumption in the process of batch rectification until separation of first grade distillate is finished. Consumption of water for condensation and cooling (W) also consists of two parts: water for stripping the feed and water used for separation of final fractions.

Two variants of stripping are considered:

– the first variant implies that the final fraction of ethanol in second final quality distilate (DKII) is 85 vol.%, and in the third final quality (DKIII) is 80 vol.%, and
– the second variant implies that the ethanol fraction is 70 vol.% in both final qualities.

Second variant is considered because when separating the final fractions there is no need to separate the distillate when ethanol concentration is over 70 vol.%, and later to add water to this distillate in order to prepare the feed for the next batch.

First variant

Based on the mathematical model of stripping, steam consumption for stripping the feed (P_1) can be presented as a function of time (τ) as:

$$P_1 = 1.067\exp(0.447\,\tau) \tag{4}$$

where: τ [h] is the time of separation of the final fractions calculated from the moment when separation of first grade distillate is finished ($0 < \tau < 14$ h):

Average steam consumption in the process of batch rectification until separation of final fractions begins is:

– P_2 = 2.35 kg/1AA in case of conventional process, and
– P_2 = 1.94 kg/1AA in case of modified (optimized) process.

Water consumption in the process of stripping the feed (W_1) can be presented as a function of time (τ) as:

$$W_1 = 0.015\exp(0.453\tau) \tag{5}$$

Average water consumption in the process of batch rectification until separation of final fractions begins is:

– W_2 = 0.037 m^3/1AA in case of conventional process, and
– W_2 = 0.030 m^3/1AA in case of modified process.

Determination of the moment after which it is no longer economically profitable to continue stripping the batch feed is done for the both conventional and modified process in the rectification column.

In case of the conventional process the eq. (4) can be written in the following form:

$$C_{\mathrm{EP}} > [1.067\exp(0.447\tau) + 2.35]C_{\mathrm{P}} + [0.015\exp(0.453\tau) + 0.037]C_{\mathrm{W}} \tag{6}$$

Based on eq. (6) it can be calculated that stripping is economically profitable until the moment τ = 7.79 h which coincides with the reflux ratio of R = 55.1 and ethanol fraction in the residue of 830 ppm (mole).

In case of modified process the eq. (3) can be written as

$$C_{\mathrm{EP}} > [1.067\exp(0.447\tau) + 1.94]C_{\mathrm{P}} + [0.015\exp(0.453\tau) + 0.030]C_{\mathrm{W}} \tag{7}$$

from here, economically profitable stripping time is τ = 7.81 h, which coincides with the reflux ratio of R = 57.4 and ethanol fraction in the residue of 800 ppm (mole).

Second variant

In this case, the characteristic equations of the process are

$$P_1 = 1.005\exp(0.453\tau) \tag{8}$$

and

$$W_1 = 0.0155\exp(0,453\tau) \tag{9}$$

Replacing (8) and (9) in eq. (3) yields economically profitable stripping time of τ = 7.81 h (reflux ratio R = 41.4, ethanol concentration in residue 800 ppm (mole)).

It is stated in [24] that the reflux ratio value at which it is no longer economically profitable to continue separating the distillate is 15-30.

It must be mentioned that stripping in the process of continuous distillation is greater than in the process of batch rectification. Ethanol fraction in the residue, when process of continuous distillation is observed, is within 40-50 ppm (mole), while in case of batch rectification with stripping, the process is stopped when ethanol fraction in the feed reaches 800 ppm (mole).

Production of absolute alcohol

For most industrial and fuel uses, the rectified ethanol (96.2 vol.%) must be purified. For the production of pure ethanol (99.9%vol.) some of these procedures can be used:

- permeation,
- pervaporation,
- azeotropic distillation, and
- adsorption.

The cost of additional purification, which was expressed per lAA, is 0.012-0.044 €/lAA, depending on the applied procedure. On the basis of these data, production cost of absolute ethanol is:

- 0.5654-0.5974 €/lAA (conventional procedure), and
- 0.5464-0.5784 €/lAA (optimized procedure).

Conclusions

The basic goal of this study was to increase energy efficiency of the distillery that produces rectified ethanol and has the capacity of 4000 lAA per day. Energy savings were considered in the plants for continuous distillation and for batch rectification.

In case of optimized process in these two plants, savings at continuous distillation plant is 11.2% (475.5 t of steam per year and 396 m^3 of water per year) and savings at batch rectification plant is 16.9% (541.2 t of steam per year and 924 m^3 of water per year). This means that for both plant steam consumption is decreased by 1017 t/year, and process water consumption is decreased by 1320 m^3 per year. This means that total savings of 25100 € per year can be made. It should be noted that the above analysis refers to the medium-sized plant.

Based on the results of the techno-economic analysis it is established that ethanol production price is greater in Serbia than in EU and USA. This comes as a consequence of greater energy-generating products costs in Serbia.

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Nomenclature

a – amortization rate, [year^{-1}]
C_1 – investment cost of the existing plant with the capacity S_1, [€/(lAA/year)]
C_2 – investment cost of the new plant with the capacity S_2, [€/(lAA/year)]
C_{EP} – ethanol selling price, [€/1AA]
C_{inv} – overall investment costs, [€/(lAA/year)]
C_{ope} – operating costs, [€/lAA]
C_P – steam price, [€/kg]
C_{tot} – overall year expenses, [€/lAA]
C_W – water price, [€/m^3]
n – exponent, [–]
P – steam consumption, [kg/1AA]
P_1 – steam consumption for stripping the feed, [kg/1AA]
P_2 – average steam consumption in the process of batch rectification until separation of final fractions begins, [kg/1AA]
R – reflux ratio, [–]
S_1 – capacity of the existing plant, [lAA/year]
S_2 – capacity of of the new plant, [lAA/year]
W – water consumption for condensation and cooling in the process of batch rectification, [m^3/1AA]
W_1 – water consumption in the process of stripping the feed, [m^3/1AA]
W_2 – average water consumption in the process of batch rectification until separation of final fractions, [m^3/1AA]

Greek symbols

τ – time of separation of the final fractions calculated from the moment when separation of first grade distillate is finished, [h]

Acronym

lAA – liter of absolute alcohol

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