EXERGOENVIRONMENTAL ANALYSIS OF THE ANHYDROUS ETHANOL PRODUCTION PROCESS IN AN AUTONOMOUS DISTILLERY

José Carlos Escobar Palacio[a*], Electo Eduardo Silva Lora[a], Maria Luiza Grillo Renó[a], José Joaquim Conceição Soares Santos[b], Mateus Henrique Rocha[a], Osvaldo Jose Venturini[a]

[a]Federal University of Itajubá, Itajubá – MG, Brazil
[b]Federal University of Espírito Santo, Vitória-ES, Brazil

[*]Tel (+5535)3629-1466, Fax (+5535) 3629-1355, jocescobar@unifei.edu.br

Abstract. According to the Life Cycle Assessment (LCA) methodology, allocation is required for multi-product processes. In the ethanol life cycle this refers to six sub-processes: sugarcane milling, juice treatment, evaporation, fermentation, ethanol purification and electricity generation. In these processes an allocation based on the exergy of the main streams was applied.This was done trought an exergoenvironmental evaluation of ethanol production process from sugarcane, considering an autonomous distillery plant with a milling capacity of 1,672,000 t/year using thermoeconomics and life cycle assessment (applying the Eco-Indicator 99 method). The results allowed determining which stages of ethanol production process present the greatest environmental impacts, and the possibilities to minimize these impacts.

Keywords: Anhydrous Ethanol, Autonomous distillery, Exergoenvironmental analysis

1.- INTRODUCTION

Environmental impacts associated to the ethanol production differ widely depending of agriculture practices applied during sugarcane cultivation (refereed to the use of fertilizers, pesticides, diesel fuel spent in soil preparative, mechanized harvesting and the transportation of sugarcane to the processing mill) and how the steam and electricity needed for the production process is generated. At present, all the Brazilian plants are selfsufficient in the generation of these utilities, and in some cases produced surplus of electricity for sale using sugarcane bagasse as a fuel, instead of fossil fuels in the cogenerations systems, this allows obtaining a lower overall CO_2 emissions on a life cycle basis.

A commonly used tool for sustainability studies is LCA, which includes evaluation of inputs, products and impacts in all stages of the product life cycle. There has been a substantial development of life cycle methodologies to assess the energetic and environmental performance of product systems from cradle-to-grave. The LCA application to biofuels has some constrains that were analyzed by [5].

Since LCA is not a thermodynamic assessment there is not capable of allocating the environmental impact of fuel consumption to single components. This problem has been solved by authors suggesting an exergy analysis over the entire life cycle of a product or process, e.g., by the concept of exergetic life cycle analysis or life cycle exergy analysis, either by extensions of environmental LCA through exergy-based indicators [8].

The purpose of the work reported here is to develop a better understanding of the environmental impact formation in the anhydrous ethanol production by means of an exergoenvironmental analysis. In this study, the environmentally most relevant system components of this process are identified and information about possibilities for reducing the overall environmental impact is provided.

2.- ENVIRONMENTAL ASSESSMENT OF THE SUGARCANE PRODUCTION AND ENERGY

The most relevant isssues associated with environmental impacts of sugarcane and bioethanol production in Brazil includes emissions with global impacts (greenhouse effect gases), local impacts (especially associated with pre-harvest burning), water use and the disposal of effluents (including stillage), use of agricultural pesticides and fertilizers, erosion and protection of soil fertility and biodiversity. To quantitatively assess the environmental impact of the previously mentioned aspects and to combine it with an exergetic analysis we need a LCA method that converts the main environmental impacts in a single indicator. The LCA methodology is standardized and described under the standards of the International Standard Organization, ISO 14040–14043.

In relation the Life Cycle Impact Assessment, many methodologies to assess the human health impacts and environmental risk have been developed. One of these methodologies applied in many LCA works is the Eco-Indicator 99 (Figure 1).

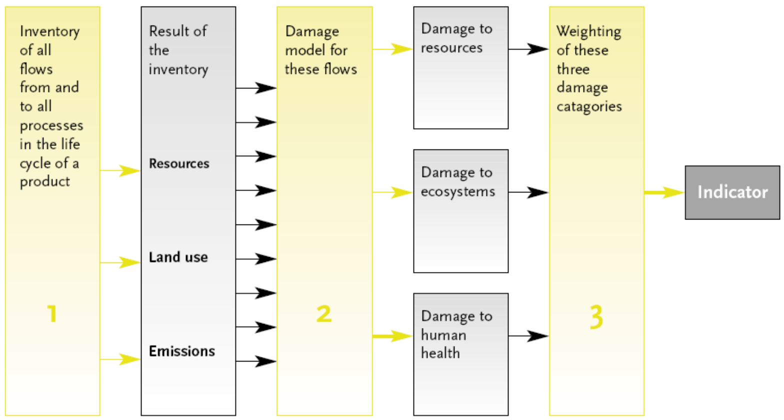

Figure 1. General procedure for the calculation of Eco-indicators. The light coloured boxes refer to procedures, the dark coloured boxes refers to intermediate results (Ministry of Housing Spatial Planning and the Environment, 2000)

This method analyzes environmental loads under three impact areas (human health, ecosystem, resources), computing eleven different impact categories like carcinogens, respiratory organics, respiratory inorganic, climate change, radiation, ozone layer, eco-toxicity, acidification, eutrophication, land use, minerals and fossil fuels.

Luo [6] carried out a comparative study of LCA on gasoline and ethanol as fuels. From the LCA results it can be concluded that in terms of abiotic depletion, GHG emissions, ozone layer depletion and photochemical oxidation ethanol fuels are better options than gasoline, while gasoline is a better fuel where human toxicity, ecotoxicity, acidification and eutrophication are concerned. When GHG emissions are concerned, however, burning bagasse for electricity generation (base case) is a much better option than converting bagasse to ethanol (future case); while in all the other aspects the results are better for the future case.

3.- EXERGOENVIRONMENTAL ANALYSIS

In the exergoenvironmental evaluation the approach of thermoeconomic analysis is modified to deal with an evaluation of the ecological impact instead of an economic problem. The exergoenvironmental analysis of this work consists mainly of three steps. The first is an exergy analysis of the energy conversion process that contains an ethanol plant and its cogeneration system for supplying thermal and electrical demand. Second, it computes the environmental impacts by applying the Eco-Indicator 99 life cycle assessment method. In last step the environmental impact are assigned to the exergy streams in the process, using thermoeconomics tool, which allows the calculation of the exergoenvironmental variables and the realization of the exergoenvironmental evaluation.

To obtain the system of equations, this paper considers the mathematical formalism used by [11].

One of results from exergoenvironmental analysis is called as specific environmental impact bj. This represents environmental impact associated with the production of the j stream per exergy unit (mPts/kJ) [8]. Similarly, it computes the environmental impact rate $\dot{B}_j$ (mPts/s) of stream j. This impact is the product of its exergy rate $\dot{E}_j$ and the specific environmental impact b_j, as Eq. (1):

$$\dot{B}_j = b_j.\dot{E}_j \qquad (1)$$

Another important variable calculated is the environmental impact of exergy destruction. As work [1], it is assumed that exergy destruction is compensated for by higher consumption of fuel to obtain the given amount of product. So, in this case the exergy destruction ($\dot{E}_{D,k}$) is multiplied by the specific environmental impact $b_{F,k.}$ associated with the fuel component. The result is the environmental impact of exergy destruction (Eq. (2)).

$$\dot{B}_{D,K} = b_{F,K}\dot{E}_{D,K} \qquad (2)$$

So, computing the specific environmental impact of all internal flows of exergy (j) through environmental impact balance of the each equipment or sub-system k from thermal system, as it is in Eq. (3).

$$\sum(b_j \dot{E}_j) = \dot{Y}_K \tag{3}$$

Where $\dot{Y}_k$ is the environmental impacts that occur during the life cycle phases of equipment or sub-system k, as example: construction (including manufacturing, transport and installation), operation and maintenance. These environmental impacts use the Eco-Indicator 99 method for calculation, after it divides the results by lifespan of equipment. In this study assumed the lifespan of all equipments at 100,000 hours.

4.- PLANT DESCRIPTION

During ethanol production from sugarcane in an autonomous distillery (i.e., not annexed to a sugar mill), the feedstock is washed, crushed and milled to extract the sugarcane juice and that resulted in a co-product (bagasse). The sugarcane juice is transformed into ethanol according to the following stages: juice treatment, concentration and sterilization; fermentation; distillation and dehydration (see Fig. 2).

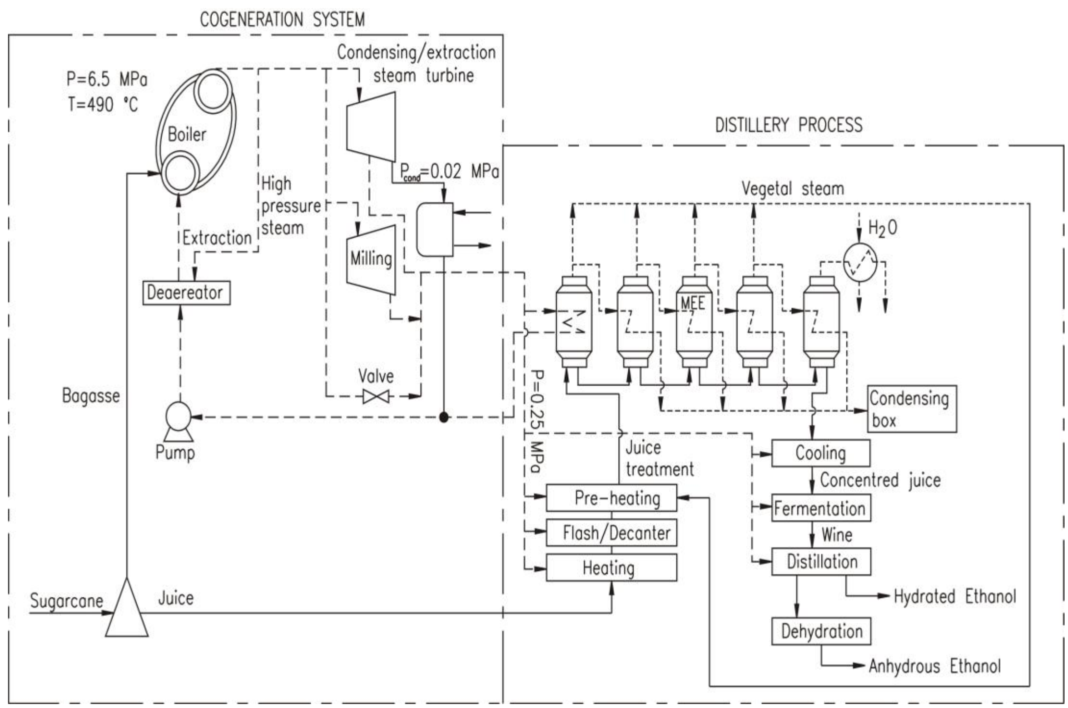

Figure 2. Physical structure of autonomous distillery

In this study, the cogeneration plant is based on condensing/extraction steam turbine (CEST). Mills are driven by simple stage steam turbines, the evaporation system is a four effects one, and the plant also has continuous fermentation, atmospheric distillation and dehydration system based on cyclohexane. The steam is generated in two boilers at steam parameters of 6.5 MPa and 490 °C. The cogeneration plant simulation was carried out, considering the parameters presented in Table 1, using the Gate-Cycle software.

Table 1 - Parameters adopted for the process simulation

Parameter	Value	Units
Cogeneration plant		
Atmospheric air temperature	25	°C
Atmospheric air pressure	101.3	kPa
Steam pressure	6.5	MPa
Steam temperature	490	°C
Condensing pressure	20	kPa
Bagasse moisture content	50	%
Sugarcane fiber content	14	%
Bagasse - Low Heating Value (LHV)	7560	kJ/kg bagasse
Boiler thermal efficiency	82*	%
Steam turbines isentropic efficiency	80	%
Pump isentropic efficiency	85	%
Electric generator efficiency	96	%
Process electric power consumption	12	kWh/tc
Cogeneration plant auxiliary equipment power consumption	**	
Mills		
Mills capacity	380	tc/h
Inlet steam pressure	2.2	MPa
Process steam pressure	250	kPa
Mechanical power demand of cane preparation and juice extraction	16	kWh/t of cane
Steam turbines isentropic efficiency	70	%
Process steam demand		
Process steam pressure	250	kPa
Process steam temperature	124.7	°C
Process steam consumption	388	kg/tc
Hydrated ethanol production	365	m^3/d
Anhydrous ethanol production	364	m^3/d

*Based on LHV of mill wet bagasse

** Calculated for each case using the modeling software Gate-Cycle.

5.- LIMITATIONS AND ADVANTAGES OF EXERGOENVIRONMENTAL ANALYSIS

The restriction of exergoenvironmental analysis is referred to the LCA method and can be find in [4] and [10].

According the International Stand on LCA the allocation should be avoided where possible by sub-division or system boundary expansion [7]. However, when the allocation is inevitable, the ISO 14041 recommends that the allocation should reflect the physical relationships between the environmental loads and the functions. The choice and justification of allocation procedures is a major issue for life cycle assessment, especially since it can have a significant influence on subsequent results. In this way the exergoenvironmental analysis allows to allocate the main environmental loads takes into account the quality of the different kinds of energy.

6.- RESULTS

6.1- Life Cycle Assessment

The life cycle analysis of Anhydrous Ethanol starts at the stage of agricultural production of the sugarcane and ends with Anhydrous Ethanol production (Figure 3).

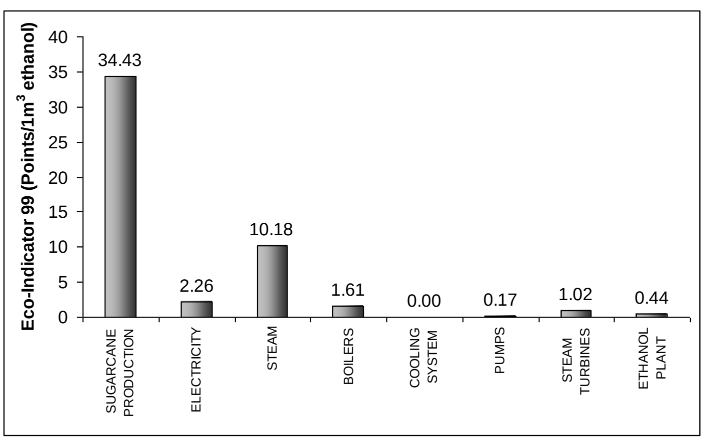

Figure 3. Total environmental impacts of the system

In this study, the Anhydrous Ethanol supply stage to distribution companies, fuel stations and to consumers was not considered. The environmental impacts of all system related to the production of 1 m^3 anhydrous ethanol, which is the functional unit of this work. The Figure 4 presents the environmental impacts divided by impact categories (carcinogens, ecotoxicity, land use, climate change, and others).

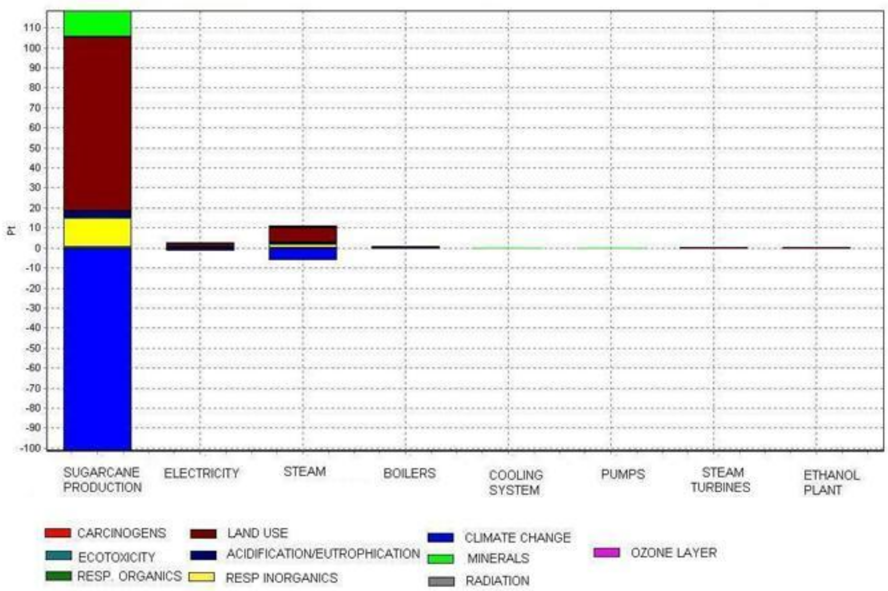

Figure 4. Environmental impacts of all system by impact categories

The Figure 4 shows that the sugarcane production presents a favorable impact for climate change mitigation, this is due to the carbon dioxide absorption by the sugarcane during its growth. Along the life-cycle of the ethanol produced from sugarcane the consumption of non-renewable energy sources is mainly influenced by diesel consumption, mainly by agricultural machines such as: harvesting machines and trucks. The energy consumption is also impacted by fertilizers herbicides and pesticides use.

6.2- Exergy Evaluation

A schematic representation about the sugarcane exergy conversion is shown in the Figure 5.

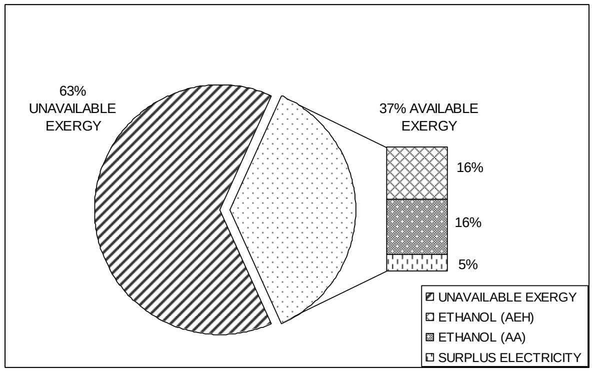

Figure 5. Available and unavailable exergy of sugarcane for the ethanol distillery

Figure 5 shows that only 37% of the exergy contained in the sugarcane is converted to surplus electricity and ethanol and the remaining 63% is lost. Increased exergy efficiency benefits the environment by avoiding energy use and the corresponding resource consumption and pollution generation. In this sense, the implementation of biorefineries in the sugar and alcohol industry can increase the sugarcane exergy utilization incorporating plants configuration that allows to obtain surplus electricity and ethanol from the lignocelullosic residues through a hydrolysis process our use the bagasse and trash for the production of biofuels using Biomass to Liquid (BTL) technologies.

Lignocellulosic biomass such as crop residues and sugarcane bagasse have the potential to meet the future demand for ethanol feedstocks. Thus, the biorefinery is as a way to mitigate the environmental problems, since it provides effective solutions to the better utilization of the sugarcane energy with positive economic impacts.

6.3- Exergoenvironmental Analysis

Table 3 shows the main results of exergoenvironmental analysis that allow identifies the process components that should be considered first to improve the global process of ethanol production (cogeneration system and ethanol process). For the calculation of the environmental impact of exergy destruction and system components was considered that the ethanol plant is composed by the following stages: heating, evaporation, cooling, fermentation, distillation and dehydration, this was made because the environmental impacts that of these stages including construction (including manufacturing, transport and installation), operation and maintenance was found for the whole production process and not for each stage for separate. For the cogeneration system was possible to make this separation of components in boilers, pump system, cooling system, steam turbines and condensers (ST+C) due to the availability of information.

Table 3. Environmental impact of exergy destruction and from system components

Equipment	$\dot{Y}_K$ (mPts/s)	$\dot{B}_{D,K}$ (mPts/s)
Boilers	4.48x 10^{-9}	1.13x 10^{-7}
Pump system	4.77x10^{-10}	5.34x 10^{-11}
Cooling system	1.46x10^{-12}	3.75x 10^{-10}
ST1 + C1	1.41x10^{-9}	1.01x 10^{-8}
ST2 + C2	1.41x10^{-9}	2.54x 10^{-9}
Ethanol plant	1.22x10^{-9}	3.85x 10^{-8}

The results obtained in the exergoenvironmental analysis shows that the environmental impact caused by exergy destruction ($\dot{B}_{D,K}$) is the main source of environmental impacts in the autonomous distillery when compared with the component-related environmental impact of the system ($\dot{Y}_k$) that were very low.

The values of the environmental impacts due to exergy destruction show that major environmental impacts associated with exergy destruction occur in cogeneration plant components followed by the ethanol plant. Technological alternatives for reduce the exergy destruction in the cogeneration plant are: (i) Increase the steam parameters from 6.0 up to 12.0 MPa. However, in spite of, the steam parameters of 12,0 MPa can reduce the exergy destruction in the cogeneration system, actually these steam parameters not represent the best economic attractiveness when compared with cogeneration plants operating with steam parameters of 8.0 MPa [2]. In the future a more reductions can be achieved incorporating a Biomass Integrated Gasifier Gas Turbine/Combined Cycle BIGGT. (ii) In the ethanol plant the environmental impacts due to exergy destruction can by reduced by the adequate control of the fermentation process together with a multipressure distillation for hydrated ethanol production and molecular sieves for dehydration and incorporating diffusers or electrical drives in the mills [3].

7.- CONCLUSIONS

In this paper, an autonomous distillery plant was evaluated using an exergoenvironmental analysis. The results shows that the environmental impact of the exergy destruction within all components of the autonomous distillery plant is higher than the component-related environmental impact. This means that the overall environmental impact can be reduced by reducing the exergy destruction within components, even if this would require efficient modern equipment items in the whole plant such as: diffuser or electrical drives in the mills, multi pressure distillation and molecular sieves in the dehydration system.

Through the incorporation of new configurations of sugar and alcohol plants (biorefineries) it's possible the diversification of the main products obtained in the plants (surplus electricity and liquid fuels trough lignocelullosic residues) that allows obtain a better sugarcane exergy this will help in long-term sustainability of the Brazilian sugar and alcohol industry.

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