

POLYGENERATION SYSTEM IN THE SUGAR AND ALCOHOL INDUSTRY

Gustavo Ferreira de Souza, gustavo@rajunior.com.br¹
José Carlos Escobar Palacio, jocesobar@gmail.com¹
Dimas José Rua Orozco, dimas.rua@hotmail.com¹
Oscar Almazán del Omo, oscar.almazan@icidca.edu.cu²
Electo Eduardo Silva Lora, electo@unifei.edu.br¹

¹ Universidade Federal de Itajubá. Av. BPS 1303, Pinheirinho, Itajubá-MG, Brazil.

² Instituto Cubano dos Derivados da Cana-de-açúcar (ICIDCA), Cuba

Abstract. *The conventional installations of sugar mills and annexed or autonomous distilleries are engineered including an installation to generate the thermal and electric energy demanded by the processes. It's common that the surplus electric energy be sold to the grid improving, in this way, the economic balance of the factories. However, sugar mills and distilleries have wastes that must display their potential through wise ways of use, considering the ecological concerns and the enforcement laws, aside from economic opportunity. Bagasse as the fibrous residue of the sugarcane milling, constitute not only a "green" fuel, but also the raw material for the production of more ethanol by the Second Generation processes. Also, the production of bioethanol in annexed or autonomous distilleries generates a waste – the vinasse – of a very high pollutant potential. The present paper deals with the study of an industrial arrangement that allows to combine the cane sugar, ethanol and protein rich concentrate production at a low environment impact, with improved energy efficiency, making available the full production potential of co-products and wastes, like bagasse from sugarcane milling and vinasse from bioethanol production, to obtain cane sugar, surplus electricity, bioethanol by first and second generation processes and a very demanded fodder protein concentrate. Two Scenarios, as Cases, are analyzed. A set of indicators are used to compare the alternatives:*

- (i) *Global efficiency as the rate of sum of products energy / sugarcane energy (%)*
- (ii) *Energy productivity / ha (GJ/ha)*
- (iii) *Increased land availability by substituting grass for vinasse-yeast in animal feeding (ha)*

Keywords: polygeneration, bioethanol, animal feed.

1. INTRODUCTION

A typical process industry doesn't consist of separated units but of a combined net of individual units that share mass and energy. When it comes to optimize the system energy use, looking for a better use of the natural resources, with less environmental impacts, it's necessary to employ a global approach that considers the interaction within the systems.

The utilization of the by-products of sugarcane industry allows the development of the industry on a close cycle of integral use of the resources, employing the wastes, using them to reduce the environmental damage and to obtain valuable products.

Polygeneration (Figure 1) is defined as the production of two or more energy services or/and manufactured products, reaching the maximum potential of the resources (Serra et al. 2009).

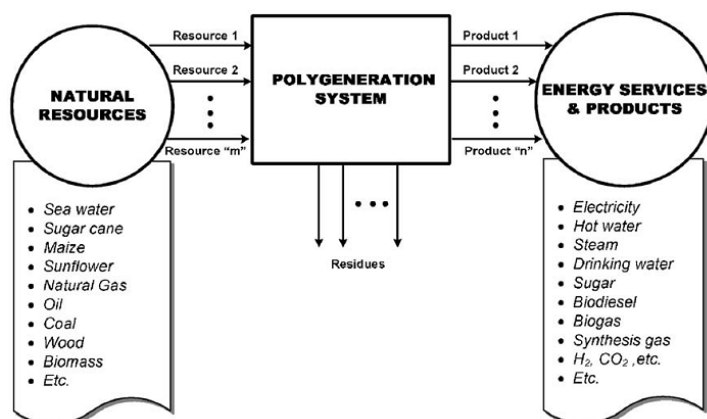


Figure 1: Polygeneration generic diagram. Serra et al. 2009.

In the case of Sugarcane it's possible to identify two main lines of production: sugar or biofuels. The optimum exploitation of this renewable raw material, can lead to increasing the quantities of sugars, surplus bagasse as fuel, intermediate molasses and juices as substrate for biofuels, deciding the most convenient production scheme on the demand and prices. In the existing production arrangements is possible to introduce technological industrial changes, which may be accompanied by other in the agriculture, mainly in growing and harvesting, new sugarcane varieties that expand the yield of sugar per hectare, the extension of the harvesting and planting seasons and also some of the new ones for specific purposes, like the energetic cane, with higher fiber content as a way to increase the amount of bagasse that can be used as fuel and as raw material for the production of pulp and paper, boards, molded elements, etc. The present paper focus on two Cases of Study where a traditional sugar mill with an annexed ethanol plant is compared with another sugar mill, also with annexed distillery, but that uses the sugarcane bagasse not only as fuel but as a lignocellulosic raw material to produce bioethanol by the bio chemical route on a Second Generation Technology, using the residual vinasse to produce animal feeding protein.

2. GENERAL ASPECTS

2.1. Energy uses of sugarcane

Sugarcane have a energy content of about 7.3 GJ/t divided into stalk fiber (bagasse), sugar and fiber of the straw (Leal, 2004; BNDES & CGEE, 2008), and 1 ton of sugarcane is equivalent to 1,2 crude oil barrel in terms of energy content (figure 3).

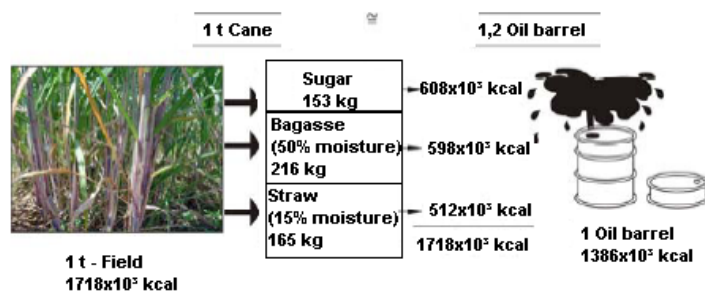


Figure 2. Energetic view of sugarcane. Adapted from Olivério (2003).

It's clear that more than a half of the sugarcane energy concentrates on bagasse and straw, and their use to generate energy and byproducts is an important approach for the sugar and alcohol sector. The bagasse, once used to generate steam and power as boiler fuel, could be used also as feedstock to 2nd generation ethanol production, among other byproducts.

The straw, once burned in the fields to facilitate harvesting, could be lead to have a fraction maintained unburned in the field as soil conditioner assisting in pest control and the other fraction used as boiler fuel partially replacing bagasse, which generates more electricity surpluses and/or lignocellulosic ethanol.

2.1.1. Diversified Mills

Sugar cane can have different uses, assuming take advantage of it rationally. This cultivation as well as producing sugar in a period of time, is flexible to change with different purposes. It is about using more efficiently its carbohydrate content, its energy character and the yield of green matter to maximize its use.

The use of alternative schemes will produce the optimum sugarcane processing to obtain, along with sugar, larger quantities of bagasse, intermediate molasses, juices, regarding the demand and the options that are more convenient production.

These alternatives are possible variations to introduce in the technological changes of the intermediate products, which may be accompanied by other changes in the growing and harvesting of sugarcane in the off season periods, and planting varieties for specific purposes.

The production of derivatives should focus, whenever conditions permit, combining with sugar through "integrated technological schemes", linked from the technological, energy and services point of view.

These schemes should be designed as a close technological cycles, so take advantage of all waste for conversion into useful products, while recycled water within the factories to avoid environmental contamination.

The "production alternatives" (Table 1) should be chosen according to the particular conditions that enable the highest possible revalorization of the cane and its by-products as raw materials. It should also consider the alternative uses of sugarcane varieties with features aimed at the production of derivatives.

Due to the characteristics of the cane as efficient source of metabolic energy, it has special conditions to meet the requirements of the direct use as "feed" or using crop residues to industrial byproducts.

2.2. Conventional sugar and alcohol production

Almost all sugar and ethanol produced in Brazil comes from the sugarcane.

Sugarcane has two main parts: the fiber (insoluble material from the whole plant) and the juice (water and soluble solid materials where the sugars are).

The harvesting operation is performed in correspondence with the milling capacity of the factory, it's important that the harvesting operation supply enough cane for a uniform and continuous supply to the mill to ensure that it will operate at full capacity, for maximum efficiency and quality, by always using fresh sugarcane.

Coming to the mill, the cane weighed, sampled, unloaded and storage, being ready to go to the extraction station, where the sugar juice is recovered.

The juice extraction can be done by milling and by diffusion, after being extracted the juice is dividing into two streams, one goes for sugar production and the other to be fermented and distilled for the production of bioethanol (IPT, 1990).

Ethanol can be produces from saccharine raw material like sugarcane, sweet sorghum and sugar beets juices and also from starchy raw materials like cassava, sweet potato, corn and other grains, and lignocellulosic raw materials such as wood, agricultural residues and sugarcane bagasse.

On the other hand, sugar production is a physical process (no chemistry involved) consisting practically in the concentration of the juices by evaporation, up to the point where supersaturated carbohydrate solutions allows the sucrose crystallization (IPT, 1990; Dias, 2009).

2.3. Second Generation Ethanol Production

Sugarcane bagasse is the lignocellulosic portion of sugarcane wich has an average composition like shown on Table 1.

Table 1. Average bagasse composition

Composition	% (Dry basis)
Celluloses	46,6
Pentoses	25,2
Lignin	20,7
Organosoluble	2-3
Aqueous soluble	2-3
Ash	2-3
Moisture	48-52

To produce bioethanol from lignocellulosic materials it is necessary a more complex procedure, starting with a pretreatment to destroy the crystalline structure of cellulose, hemicellulose and lignin, to give way to the action to obtain the fermentable monosaccharides.

In the saccharification step acids or enzymes can be used to hydrolyze the large glucose and pentose polymers to hexoses and pentoses monosaccharides, so they can be fermented to ethanol. Higher yield in terms of alcohol are generally obtained with the enzymatic hydrolysis.

Available technologies are under development to perform the saccharification or/and the simultaneous hydrolysis/fermentation (SSF, simultaneous sacharification and fermentation) or the separate alternative (SHF separated hydrolysis and fermentation) and (SSCF, simultaneous sacarification and co-fermentation) (Coral, 2009; Sun and Cheng, 2002).

2.4. From bioethanol waste to a protein-rich feedstock

The bioethanol production by the anaerobic fermentation of the sugarcane carbohydrates renders an organic matter rich residue: the vinasses.

Vinasses are produced at a rate of 10 to 16 cubic meters for cubic meters of distilled ethanol. Chemical oxygen Demand (COD) of vinasses varies slightly according to fermentation and distillation efficiencies, but roughly stays from 70 to 80 kg/m³. The first lab approaches to the utilization of vinasse for the propagation of microbial biomass can be tracked back to the late 60s. The reduction of organic load and at the same time the production of valuable and scarce protein is the best feature of this process. Yeast biomass from vinasse showed a composition and amino acid profile very similar to those previously obtained from molasses medium. Nutritional test demonstrated that vinasse's yeasts are an excellent source of proteins for animal feeding (Otero et al., 2007). Figure 3 shows the main technological steps to obtain an animal protein from vinasse.

This organic richness of vinasse being an environmental threat could become a precious advantage, when used to be a source of energy and carbon for the biosynthesis of microbial biomass by the aerobic propagation of yeast cells. The

conversion of those wastes of the bioethanol distillation into a high quality fodder protein concentrate, gives also the complementary benefit of a sensible reduction - of more than 85% - of its contamination potential. The composition of the vinasses does not vary significantly from factory to factory, so it's possible to present, in Table 2, an average vinasse composition.

Table 2. Average vinasse composition

Component	%
Dry Matter	7.0 - 7.5
COD (kg/m ³)	70 - 80
pH	4.5 - 4.7
Total Reducing Sugars	1.7 - 2.3
Glycerol	19 - 21
Nitrogen	0.07 - 0.09
Ash	1.3 - 1.5

No doubts, with the strategy out lined in the present studies, the production of a concentrate of Single Cell Proteins (SCP) from the residual vinasses from the ethanol distillation, becomes an option of special appeal, making better economic balance and also giving a “greener” bioethanol.

To give an idea of sizes, an ethanol distillery with a capacity of 200,000 l/day, will give vinasses for the operation of a protein synthesis installation of 50 t/day of a protein concentrate of 92% dry matter, 45% crude protein.

When considering the whole “close circuit”, it's necessary to take into account that the protein factory also has wastes no matter with a reduced COD from 70-80 kg/m³ to 10-15 kg/m³. So, the most appropriate way will be to combine the alternative of protein biosynthesis with the ferti-irrigation. To have an idea of the benefits, the vinasses from the yeast factory can “return” to the soil 4kg of nitrogen, 3kg of P₂O₅ and 2kg of potassium, from every m³ of bioethanol produced, that means the 13%, the 60% and the 67% respectively of the demand of the soil for a food crop. In other words, in this way is possible to get fodder proteins and fertilizers from a thread.

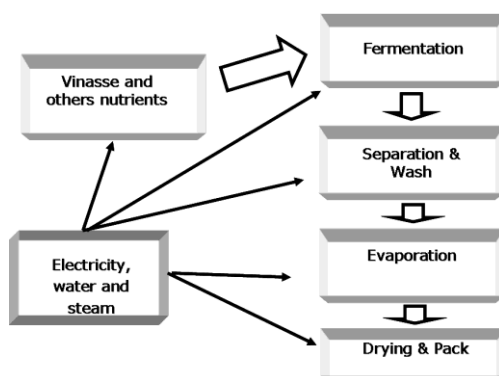


Figure 3. Vinasse – Yeast technology

The yeast can substitute with advantage, because of its high protein content a fraction of grass, in the feed of cattle grazing on pasture and thereby potentially release land for increased sugarcane production, with minimal land use change effects. A similar approach was made by Mathews et al (2011).

3. CASE OF STUDY

3.1. Case of Study I – Conventional Sugar mill and annexed alcohol distillery, with electricity surplus

Case I (figure 4) consists of a conventional sugar and ethanol plants, with a milling capacity of 500 t/h of sugarcane; where 50% of the sugarcane juice is used to produce sugar and 50% to produce hydrated ethanol. The plants operate 4,320 hours during the sugar season, when 34% of the available straw is collected from the field and used as boiler fuel, increasing, in this way, the surplus bagasse to be used for electrical generation in off season, or to be sold.

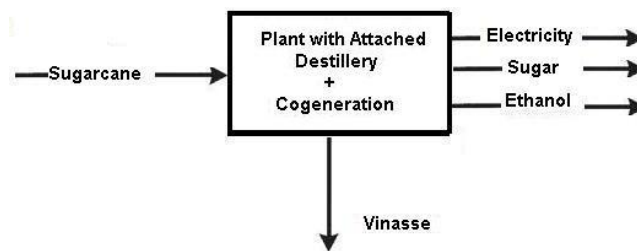


Figure 4. General scheme of the conventional sugar mill and annexed alcohol distillery.

3.2. Case 2 – Sugar mill and annexed alcohol distillery producing 1st and 2nd generation Ethanol, with electricity surplus and producing fodder protein from vinasses

Case 2 (figure 5) consists of a sugar mill and annexed alcohol distillery, using the biomass cropped in the harvest period (4,320 hours) to produce sugar, conventional ethanol, surplus electricity and using the surplus bagasse to produce 3,413 l of 2nd Generation bioethanol per hour, which uses the facilities of the distillery for 1st Generation bioethanol, with investment required, only on the pretreatment system of the lignocellulosic material.

A plant that carries a steam explosion pretreatment of the lignocellulosic material, enzymatic hydrolysis and simultaneous saccharification and fermentation (SSF) was considered. An auxiliary boiler is added for the combustion of lignin cake recovered from the pre-treatment step, improving the fuel balance for the 2nd generation ethanol production.

The vinasses produced 2nd generation ethanol plant were not considered to fertigation due to their different composition from those of conventional alcohol destillery, as well from those resulted of vinasse-yeast processes.

Only a portion of vinasses is used in the animal feed plant, with a capacity of 10-40 t/day of yeast according to parameters described by Almazán et. al (1982).

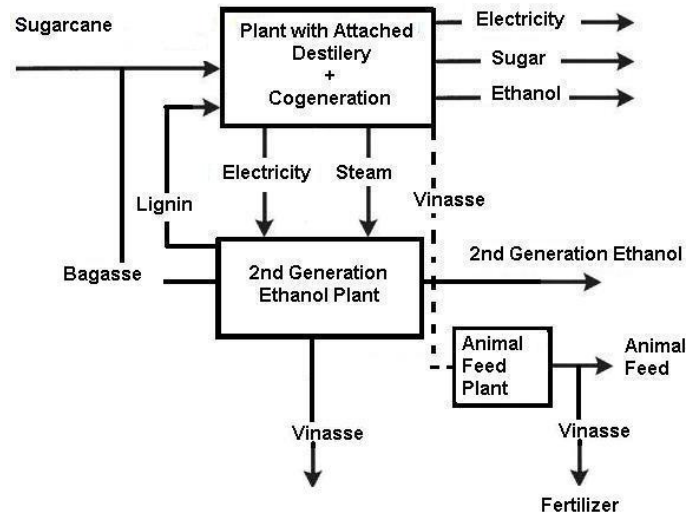


Figure 5. General scheme of a Sugar mill and annexed alcohol distillery, producing 1st and 2nd generations Ethanol, electricity surplus and animal feed from the vinasses.

Table 3 shows the main parameters considered for the plant simulation on Gate Cycle software for both Cases of Study.

Table 3. Parameters used on the plant simulation.

Parameter	Value	Units
Cogeneration plant		
Atmospheric air temperature	25	°C
Atmospheric air pressure	101.3	kPa
Steam pressure	8.5	MPa
Steam temperature	510	°C
Condensing pressure	20	kPa

Bagasse moisture content	50	%
Sugarcane fibre content	14	%
Straw recovered from field	34	%
Bagasse +Straw– Low Heating Value (LHV)	8,388	kJ/kg bagasse equivalent
Lignin recovered for cogeneration plant use	16	% of bagasse used for 2 nd gen. ethanol
Lignin – Low Heating Value (LHV)	16,219	kJ/kg
Boiler thermal efficiency	85	%
Steam turbines isentropic efficiency	80	%
Pump isentropic efficiency	80	%
Electric generator efficiency	96	%
Process electric power consumption	18	kWh/tc
Process electric power consumption (2 nd generation ethanol)	7.52	kWh/tc
Process electric power consumption (vinasse-yeast)	1,300	kWh/t of dry yeast
Mills		
Mills capacity	500	t _c /h
Inlet steam pressure	1.6	MPa
Process steam pressure	0.25	MPa
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	0.25	MPa
Process steam temperature	124.7	°C
Process steam consumption (first generation + concentration of juice)	500	kg/tc
Ethanol yield (first generation)	85	l/tc
Pretreatment steam consumption (second generation)	0.352	kg/kg of Bagasse
Ethanol yield (second generation)	0.148	l/kg of Bagasse
Process steam consumption (vinasse-yeast)	2.24-8.97	kg/tc
Animal food plant yield	0.017	t/m ³ of vinasse

4. PERFORMANCE INDICATORS

The two different alternatives were modeled using Gate-Cycle Enter software. From these models it was possible to calculate the so called “Performance Indicators”. The indicators chosen for this analysis were:

- E_{exc} [kWh/t_c]: Electricity surplus index
Calculated from the surplus power of cogeneration plant.
- η (%): Global efficiency
Calculated as ratio: sum of products energy/ sugarcane energy.
- P (GJ/ha): Energy productivity per hectare
Considering yield of sugarcane being 600 GJ per hectare (Leal, 2004) and the global efficiency of each case, $P = (\eta \cdot 600)$ [GJ/ha].
- L [ha]: Land released by the substitution of the animal feed obtained from cattle areas by vinasse-yeast, considering that 1kg of fodder yeast produced means 1 kg of grass land released, with yield of grass 4t/ha.

5. MAIN RESULTS

Table 4 shows the results of the Performance Indicators values when the simulation was carry.

Table 4. Main results

Indicator	E_{exc} (kWh/t _c)	η (%)	P (GJ/ha)	L (ha)
Case 1	89.00	33.20	199.2	0
Case 2	67.09	34.74	208.4	1,800

The values obtained that the plant arrangement in the Case of Study 1 gives an electricity surplus of 89 kWh per ton of milled cane, the value decreases around 25% in the Case of Study 2 mainly because of a higher steam demand of the 2nd Generation ethanol and vinasse-yeast technologies.

The improved use of the natural resources and residues of the plant in the Case of Study 2, using bagasse to make biofuel and the residual vinasses to produce yeast for animal feeding, lead to a higher global efficiency value (33.2 to 34.74 %), and higher Productivity per hectare (an additional 9.2 GJ/ha) which means that the thermodynamic losses are being reduced due to better use of sugarcane as a whole.

Chart 1 and 2 show the role of products and byproducts of sugarcane energy use in cases 1 and 2.

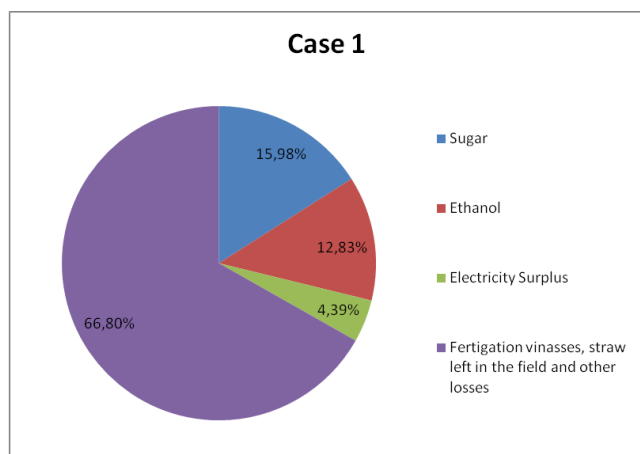


Chart 1. Sugarcane energy use in case 1.

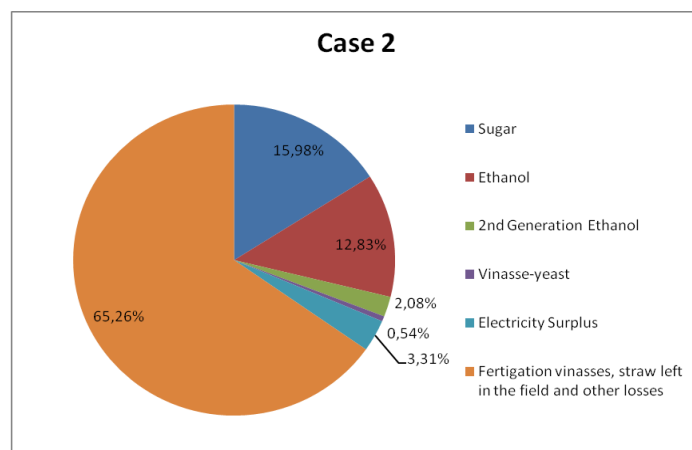


Chart 2. Sugarcane energy use in case 2.

Charts 1 and 2 show a better usage of sugarcane energy, about 1.54% which means 1.12 MJ reduction in energy losses with polygeneration, producing 2nd generation ethanol and fodder yeast from vinasses.

There is still a potential for waste recovery, which represent about 65% of total cane energy, turning them into raw material to obtain other valuable products. Among these losses, the vinasse represents greater potential for use as the 66% straw left on the field is essential for the conditioning of soil and pest control.

One part of yeast produced from vinasses can take place of up to 2 parts of molasses on cattle feeding with minimal chemical changes (Lora e Venturini ,2012). Since molasses obtain great results when introduced on cow diet (Mendez, 2004), the fodder yeast from vinasses could be as good as, or even better than molasses as cattle feeding supplement.

Matthews et. al (2011) made an approach of the land released by the substitution of the animal feed obtained from grass areas by vinasse-yeast production, giving a substantial advantage in favor of the vinasses-yeast. Consequently, it's possible to state that a positive land release is the resulting advantage of the use of the vinasses for fodder protein. Since Vinasse yeast have a protein content of 45% and cattle feeding grass have a protein content of 6-10% (Pedreira e Boin, 1969; De Almeida et al., 2009), a substitution rate of 1 is a conservative assumption. This substitution could be half the grass land used to feed one cow and the results for this Case study are shown on chart 3, that shows the sensitivity for the vinasse-yeast plant size and its impact on land substitution.

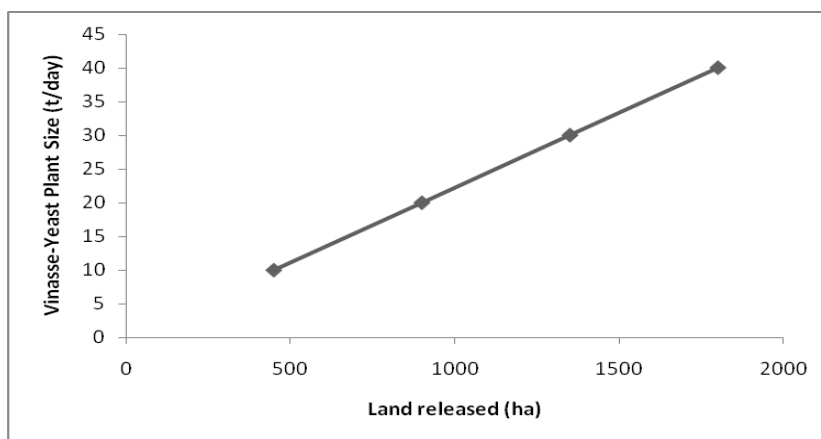


Chart 3. Sensitivity of Vinasse-yeast plant size compared to Land released.

For increased production of the yeast plant, additional land can be released to a limit of about 1800 ha for a 40 t/day plant, which means increasing up to 144,000 t of sugarcane cultivation if desired.

6. CONCLUSIONS

In the two Cases of Study, it is evident that the operation of a polygeneration system in the agroindustrial scheme requires the inclusion of the trash as complementary boiler fuel in the material balance of the whole plant. This allows maximizing the electricity generation and ensures the possibility to store enough fiber for the second generation ethanol production.

In the first Case of Study, there is a surplus bagasse from the cogeneration plant (about 10.8%) that can be burned 20 days off season for plant operation in this period, or can be sold.

The second Case of Study shows that there is a potential for utilization of waste vinasse for animal feed production, releasing land area that can be utilized for other crops; additionally this reduces the possible remaining environmental impacts that could generate by the marginal operations related to sugar and ethanol production.

The yeast production from vinasses shows that the plant can potentially release up to 1,800 ha of grass, which means 144,000 t of sugarcane can be cultivated in substitution to the grass cultivation.

With additional products obtained by the utilization of the vinasses and bagasse (Case of Study 2), the plant achieved a gain in global efficiency of 1.54% and energetic productivity gain of 4.43%. Each ha of milled sugarcane produces an additional 9.2 GJ with the polygeneration system.

The gain in efficiency and productivity per hectare of the plant shows that polygeneration is a valid way to act on reducing losses in the utilization of sugarcane energy, which can mean improvements in the profitability of the plant.

7. REFERENCES

- Almazán, O, Klibansky, M. and Otero, M. A. 1982. Producción de proteína unicelular a partir de subproductos de La industria azucarera. Monografía. Instituto Cubano de Investigaciones sobre los Derivados de La Caña de Azúcar (ICIDCA).
- BNDES & CGEE, 2008. Bioetanol de cana-de-açúcar: energia para o desenvolvimento sustentável / organização BNDES e CGEE. – Rio de Janeiro: BNDES, 2008.
- Coral, D.S.O. 2009. Indicadores Técnicos - Econômicos das Rotas Termoquímica e Bioquímica para a Obtenção de Biocombustíveis Utilizando Bagaço de Cana para as Condições Brasileiras. Dissertação de mestrado. Universidade Federal de Itajubá, Março de 2009. Itajubá-MG, Brasil.
- De Almeida, V. V. S., de Queiroz, A. C., da Silva, F. F., Silva, R. R., Oliveira, A. C., de Souza, D. R., 2009. Body composition and energy and protein requirements of grazing Nelore Steers. Revista Brasileira de Zootecnia 38,1347–1354.
- Dias, M.O.S., Ensinas, A.V., Nebra, S.A., Filho, R.M., Rossell C.E.V. e Maciel, M.R.W. 2009. Production of bioethanol and other bio-based materials from sugarcane bagasse: Integration to conventional bioethanol production process. Chemical engineering research and design 87: 1206–1216, 2009.
- IPT. 1990. Conservação de energia na indústria do açúcar e do álcool. Capítulo 3: processo de fabricação de açúcar e etanol.
- Leal, M. R. L. V., 2004. Energia na Indústria de Açúcar e Álcool: A Cana Como Fonte de Energia. Coopersucar. Disponível em: http://www.nest.unifei.edu.br/portugues/pags/novidades/curso_cyted/files/pdf/Tema%205%20-%20Producao%20e%20Uso%20do%20Etanol%20como%20Combustivel/CanaComoFonteEnergia.pdf
- Lora, E. E. S. e Venturini, O. J., Organizadores. 2012. Biocombustíveis. Vol 2. Rio de Janeiro, Editora Interciência, 2012.
- Matthews, J.A., Tan, H., Moore, M.J.B and Bell, G. 2011. A conceptual lignocellulosic ‘feedþ fuel’ biorefinery and its application to the linked biofuel and cattle raising industries in Brazil. Energy Policy 39: 4932–4938, 2011.
- Mendez, P. C. M., 2004. La alimentación Del ganado com Caña de azúcar y SUS subproductos. Editora Del instituto de ciência animal, EDICA. 1ª impressão em español, marzo de 2004. La Habana, Cuba
- Olivério, J. L., 2003. Fabricação nacional de equipamentos para a produção de álcool e cogeração. Seminário – Álcool: Potencial Gerador de Divisas e Empregos. Rio de Janeiro, 25 de Agosto.
- Otero, M.A.; Saura, G.; Martínez, J.A.; Almazán, O.A. 2007. Fodder yeast production: a new approach for distillery vinasse treatment. Proc. Int. Soc. Sugar Cane Technol., 26: 1127-1133, 2007.
- Pedreira, J. V. S.; Boin, C. Estudo do crescimento do capim Elefante, variedade Napier (Pennisetum purpureum, Schum) Bol. Ind. Animal, Nova Odessa, 26: 263-73, 1969.
- Serra, L.M., Lozano, M., Ramos, J., Ensinas, A.V. e Nebra, S.A. 2009. Polygeneration and efficient use of natural resources. Energy 34: 575–586. 2009.
- Sun, Y. e Cheng, J. 2002. Hydrolysis of lignocellulosic materials for ethanol production: a review. Bioresource Technology 83: 1–11, 2002.

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.

9. ACKNOWLEDGEMENT

The authors would like to thank FAPEMIG for financial support.