AN UP-DATE OF COGENERATION EFFICIENCY AND ECONOMIC INDICATORS USING MODERN COMMERCIAL TECHNOLOGIES

By

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KEYWORDS: Ethanol, Cogeneration, Production Cost.

Abstract

A SCENARIO considering capacity, parameters and commercialisation prices for cogeneration systems equipment was carried out, different Brazilian manufacturing costs were considered, and related data presented in tables and figures. Using the Gate-Cycle software, cogeneration plant schemes were modelled for different ethanol distillery capacities. Using energy balances and equipment cost data, the electricity generation cost was calculated for each of the evaluated scenarios. As a result of the evaluated scenarios, indicators such as: surplus electricity index, energy utilisation factor and exergy efficiency are presented. Recommendations are presented about the most profitable scenarios considering present electricity commercialisation prices of about 56.52 US$/MWh and two ethanol market price levels: 0.30 and 0.17 USD$/L.

Introduction

According to the Ministry of Agriculture, Livestock and Supply (MAPA), a government agency responsible for the registration of the mills and distilleries installed in Brazil, 434 plants crushing 495 million tonnes of sugarcane per year were in operation in the 2007/2008 harvest. Sixteen were used for sugar production only, 167 for ethanol production and the 251 remaining plants produced both sugar and ethanol (MAPA, 2009). Most of the large plants are located in the state of São Paulo, where almost two-thirds of the Brazilian ethanol is being produced (Goldemberg, 2008).

Until 1980, sugar and ethanol plants in the state of São Paulo were using boilers with pressure between 1.2 and 2.2 MPa and were purchasing 40% of the electric power they consumed. By 1990, with the replacement of old boilers and turbines, the average steam pressure in these plants had reached 2.2 MPa, with temperatures of 300°C, levels which made the plants self-sufficient with regard to their electric power needs, and in some cases produced a small surplus for sale.

Today, these boilers are being substituted by high-pressure boilers operating in the range of 6 up to 12 MPa and, in some cases, the plant capacity is increased; as a result, energy efficiency is being increased and there is in fact a large electricity surplus that is supplied to the grid. Presently, it is assessed as approximately 1400 MW, with a forecast for 2020 of 14 400 MW (Unica, 2009).

Therefore, research about how these changes affect the production costs of the final products obtained in the distilleries (electricity surplus and ethanol) and what will be the resulting efficiency increase for the whole plant is an important aspect. By carrying out simulations using commercial software and thermodynamic tools, this study intends to determine the available surplus electricity, the global efficiency and the final production cost of the main products of an autonomous distillery, considering increases in the plant mill capacity and steam parameters. It also evaluates, from an economic point of view, each one of the alternatives proposed, considering the investment values, the operational and maintenance costs, and the revenues from hydrated ethanol and electricity commercialisation.

Finally, an analysis is carried out for the determination of the specific investment required per tonne of crushed cane, the electricity generation cost, and the NPV obtained as a function of the plant capacity and steam parameters utilised, as well as for different hydrated ethanol and electricity commercialisation prices.

General aspects

Bioethanol producers establish the minimum price for their product considering two conditions: a) to cover the production costs, which obviously include raw material and plant operational costs, as well as capital costs corresponding to production investments; and b) be equal to, or higher than the price that could be obtained if the raw materials were used in the best manufacturing alternative. Sugar and molasses are among the alternative products that can be obtained from sugarcane. The second one is a by-product of the sugarcane industry that has value as an industrial input or as animal feed (BNDES and CGEE, 2008).

Indeed, the estimation of the ethanol production costs in Brazil is quite a difficult task. First, it is important to mention that this cost varies significantly in different production regions, due to the differences in productivity and cost of sugarcane production. Not only does the productivity vary, but also the cost of sugarcane production changes according to the harvest and transportation technologies. Second, estimating the cost of the sugarcane is crucial to the ethanol cost estimation. Most studies regarding Brazilian ethanol have estimated sugarcane production cost at $10 dollars per tonne, which gives a cost of roughly $0.10 per litre of ethanol. However, this cost is considered by De Almeida *et al*. (2007) to be underestimated.

Figure 1, shows the rise of hydrated ethanol production in Brazil between 2003 and 2008 and the corresponding prices for producers (excluding taxes).

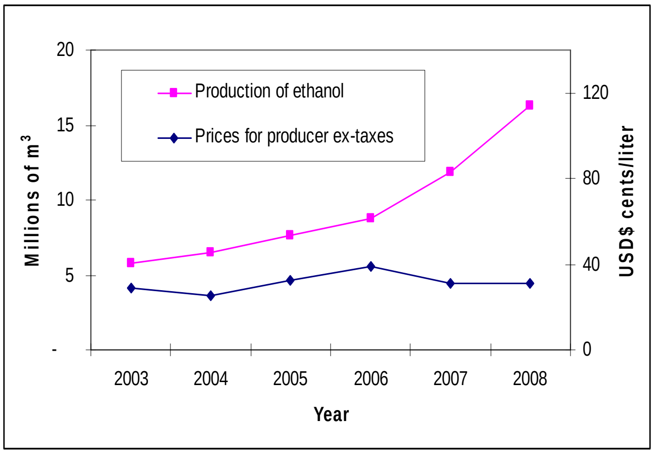

Fig. 1—Brazilian hydrated ethanol production and average prices for producer excluding taxes (UDOP, 2009 and CEPEA, 2009).

Having in mind the previously mentioned aspects, the estimation of the real ethanol production cost for the different installed plants is a very important aspect in the modernisation and expansion of the ethanol industry.

Equally, the prospect of selling electric power to public utility concessionaires requires knowledge of the real electricity production cost to calculate the economic impact of surplus electricity commercialisation in the economic balance of the distillery plant.

Process 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 in doing so a co-product is generated (bagasse). The sugarcane juice is transformed into ethanol according to the following stages: juice treatment, concentration and sterilisation; fermentation; distillation and dehydration. The sugarcane bagasse (50% moisture) is burnt in boilers for generation of thermal and electrical energy demanded by the whole plant (see Figure 2).

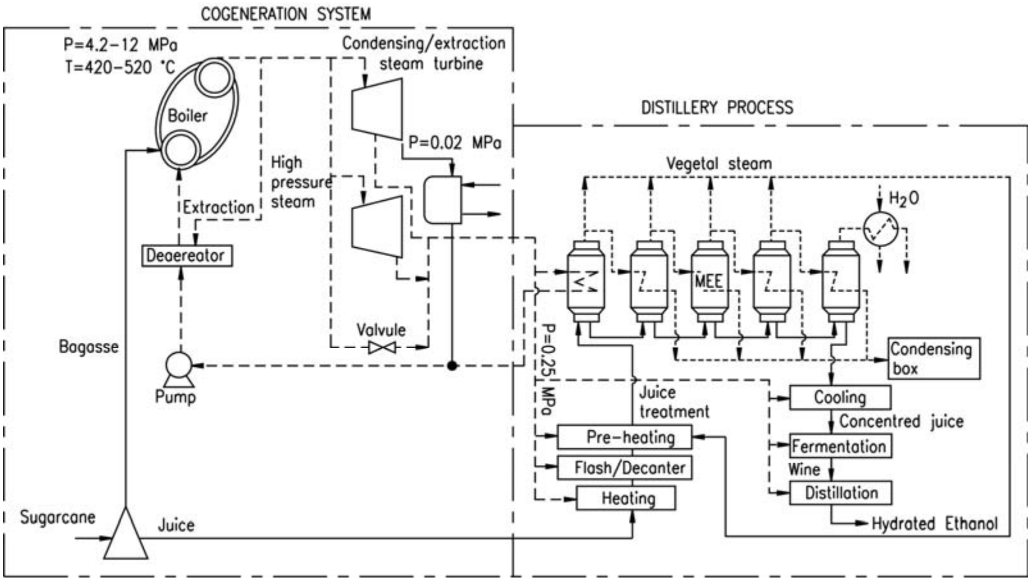

Fig. 2—Physical structure of autonomous distillery (Adapted from Higa, 2003).

Evaluated alternatives

Considering the great diversity of autonomous distilleries that exist in Brazil in relation to their milling capacity and the level of technological development of their cogeneration systems, five different autonomous distilleries with different steam parameters and capacities were considered. Their 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	4.2–12	MPa
Steam temperature	420–520	°C
Condensing pressure	20	kPa
Bagasse moisture content	50	%
Sugarcane fibre content	14	%
Bagasse – Low Heating Value (LHV)	7560	kJ/kg bagasse
Boiler thermal efficiency	88*	%
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	180–580	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
Ethanol yield	86	l/tc

*Based on LHV of mill wet bagasse

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

With respect to the electric power consumed by the different process stages (juice treatment, concentration, illumination, etc.), there are slight distinctions between processes, but all of them are around 12 kWh per tonne of processed sugarcane (BNDES and CGEE, 2008). This index was complemented with the electric power consumption of pumps and auxiliary equipments in the cogeneration systems, calculated using the Gate-Cycle software.

Performance indexes

Thermodynamic assessment

Some thermodynamic performance indexes presented by Horlock (1987) and Lora *et al*. (2006) (Eqs. (1), (2), (3) and (4)) have been considered and calculated for the different alternatives analysed in this paper. The calculated values are shown in Table 2.

Energy fuel utilisation (EUF)

This index is based on the first law of thermodynamics and allows calculating the energy efficiency of a cogeneration plant.

$$EUF = \frac{W_e + Q_u}{\dot{m}_f . LHV} \quad (1)$$

where W_e is the net electricity power output, Q_u is the useful heat rate delivered to the process and E_f is the fuel energy consumed, calculated as the product of bagasse mass flow ($\dot{m}_f$) and its low heating value (LHV).

Exergetic efficiency (η_{ex})

This index allows calculating the cogeneration efficiency based on the second law of thermodynamics, using exergy as a measure of the 'real' value, i.e., availability of an energy stream. Instead of using the process heat, this index uses the process consumed exergy, and the fuel energy is also substituted by its exergy.

$$\eta_{ex} = \frac{W_e + B_p}{B_f} \quad (2)$$

where *Bp* is the exergy of the heat delivered to the process (as steam) and B_f is the exergy of the consumed fuel (bagasse).

Global exergetic efficiency (η_g)

This indicator is obtained by dividing the sum of the exergy of the hydrated ethanol and the surplus electricity, by the exergy contained in the sugarcane (Eq. 4). It is a measure of the level of utilisation of the energy contained in the sugarcane.

$$\eta_g = \frac{E_{HE} + E_{el.ex}}{E_c} \quad (3)$$

where E_{HE} is the exergy content of hydrated ethanol; $E_{el.ex}$ the surplus of electricity and E_c the sugarcane exergy.

The sugarcane exergy content (E_c) is calculated by the Eq. 4.

$$E_C = E_B + E_{B:C} \quad (4)$$

where E_B is the bagasse exergy content and $E_{B:C}$ the sugarcane juice exergy content

Thermodynamic evaluation results

Figure 3 shows that, for each mill capacity, when the steam parameters are increased from 4.2 up to 12 MPa the surplus electricity per tonne of sugarcane crushed is increased by approximately 46%, while the exergetic efficiency of the plant is increased by 17%. It also shows the influence of the steam parameters and the distillery capacity in global exergetic efficiency of the plant. When these two factors are increased, this index is increased by approximately 3% as a consequence of the better use of the sugarcane energy content. To accomplish the necessary process steam consumption for each evaluated capacity scenario, it was necessary to consider the utilisation of turbines with different sizes and extraction/steam flow ratios. As a consequence, different values of surplus electricity per tonne of crushed cane were obtained, showing no logical tendencies. So, this is the reason why, for crushing rates of 180 tc/h, the index of electricity surplus is higher than for plants with capacities of 580 tc/h.

For steam parameters of 12 MPa, an increase of 5, 8, 9 and 11% in the global exergetic efficiency of the plant is obtained, respectively of the considered plant capacity levels.

From a thermodynamic point of view, Figure 3 shows that the better alternative, to be considered as a first option, is a distillery with steam parameter of 12 MPa/520°C and a plant capacity of 580 tc/h. A distillery with steam parameters of 8 MPa/510°C and a plant capacity of 580 tc/h can be considered as a second alternative. However, to validate the obtained result, it is necessary to carryout the economic evaluation of these alternatives.

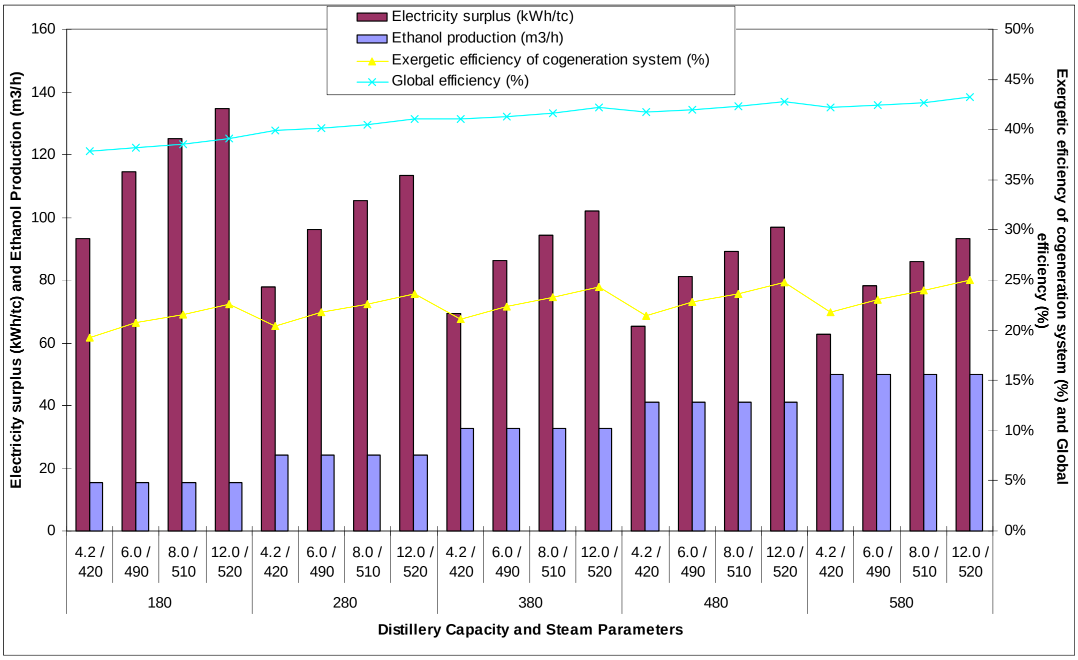

Fig. 3—Main thermodynamic indexes for the evaluated capacity and parametric alternatives.

Economic assessment

Considering that in the autonomous distillery, analysed multiple products with aggregated value (Electricity and Ethanol) are obtained, it is necessary to distribute the total costs of the plant and of the sugarcane in a rational way among them, as they will influence directly on each final product cost.

Therefore, to obtain the final production cost of electricity and ethanol, it is necessary to select the more rational cost allocation method for the products. The allocation method must generate product costs that reflect the real costs involved in its production, without overcharging one of the products (Escobar *et al*., 2009). In this work, the cost allocation method applied is based on the Second Law of Thermodynamics, using the so-called thermo-economic analysis, an approach that combines the exergy concept with economics, seeking for cost distribution (Lora *et al*., 2008). This methodology allows allocation of the input costs, as well as the investment, operation and maintenance costs of the equipment for ethanol and electricity production in dependence of the consumed exergy for its production. Figure 4 shows a schematic representation of the methodology employed for the thermo-economic assessment.

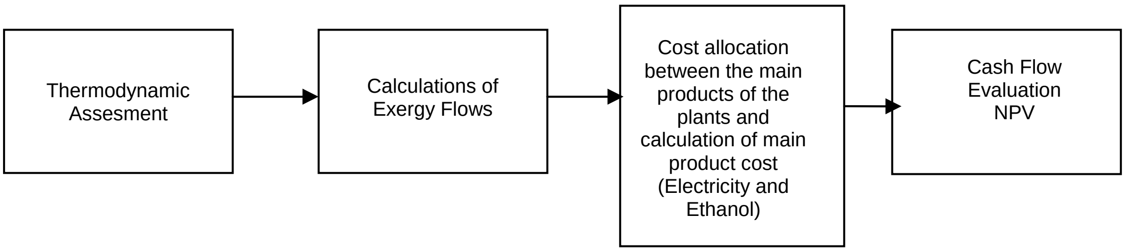

Fig.4—Thermo-economic assessment methodology flow scheme.

Cost formation

The distillery system can be considered as a system or a set of subsystems, that exchange flows (mass and energy) among themselves and between them and the environment. This information can be converted into financial or cost flow (C). The cost composition in the distillery system can be generally represented by equation (5), where the units are expressed in financial units per unit of time ($/h). In Eq. (5) the first member is the sum of input flows and the second member the outputs flow.

$$C_C + Z_{PP} = C_{ethanol} + C_{electricity} \qquad (5)$$

The input costs of the plants are the cost of sugarcane (C_c) and the fraction referred to depreciation, operations and maintenance costs of the equipment that compose the global plant (Z_{pp}). The products or output of the equation are the cost allocated to ethanol ($C_{ethanol}$) and the electric power ($C_{electricity}$). For computing the unitary costs of electricity production ($c_{electricity}$) and ethanol ($c_{ethanol}$), that are expressed in $/kWh and $/L, it is necessary to write the Eq. (5) in the form of Eq. (6).

$$C_C + Z_{PP} = c_{ethanol}.\dot{V}_{ethanol} + c_{electricity}.P_{electric} \qquad (6)$$

where $V_{ethanol}$ is the hourly produced hydrated ethanol and $P_{electric}$ is the net electric power expressed in L/h and kW, respectively.

The equipment costs that compose the plants in the different analysed scenarios were obtained from national equipment manufacturers and adapted to necessary capacities using a scaling factor. During the determination of the investment costs, some of the items necessary for the economic analysis couldn't be determined. So it was necessary to set percentages in relation to the acquisition price of different equipment (Table 2).

Table 2—Percentage values used of equipment costs used for auxiliaries, installation, civil construction and O&M during investment cost calculation (Barreda, 1999).

Cost	Value	Unit
Installation	20	%
Pipes	10	%
Instrumentation and control	6	%
Electrical equipment and material	10	%
Civil construction	15	%
Operating & maintenance	5	%

The annual interest rate considered was 8%, while the amortisation period for the equipment was assumed to be 10 years.

The autonomous distilleries specific investments for different steam parameters and plant capacities are presented in Figure 5.

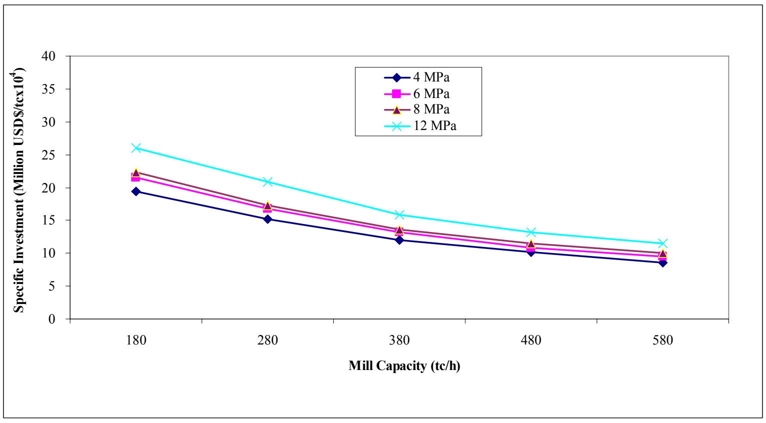

Fig. 5—Specific investment required for ethanol distilleries as a function of steam parameters and plant capacity.

With the values obtained from Figure 5, it's possible to calculate the production cost for the electricity and ethanol in different distilleries, in accordance with the productive purpose of each subsystem that comprises the global plant and the consumed and/or produced exergy in each stage. A schematic representation of the formation and cost sharing process in a distillery is shown in Figure 6.

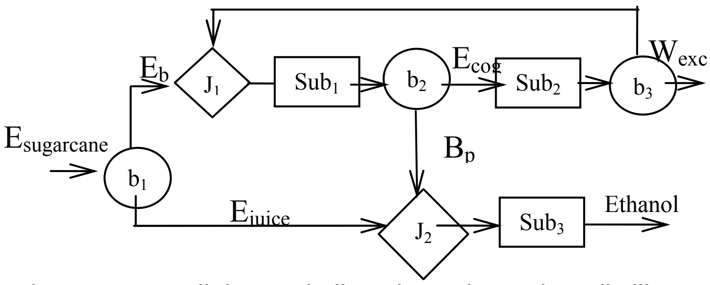

Fig. 6—Cost splitting and allocation scheme in a distillery system.

The subsystem 1 (Sub1) of Figure 6 represents all the components of the plant that supply exergy to the cogeneration cycle (pumps, boilers, deaerator, etc.), while the subsystem 2 (Sub2) represents the components that consume exergy (turbogenerators, condensers, mechanical drives). The subsystem 3 (Sub3) represents the ethanol production stages (heating, evaporation, cooling, fermentation and distillation). This allows one to follow the costs formation process of the main products of the plant (ethanol and electricity).

The Eq. (6) shows that, in a multiproduct plant, the main product costs are depending one of the other; therefore, it is necessary to allocate the sugarcane cost in a proportional way for the global system, avoiding overcharging the cost of one of the obtained products. When the bagasse cost is considered zero in the cogeneration systems, as is usually done due to its byproduct nature, the sugarcane cost will be charged fully to the sugarcane juice obtained in the mills, having as a consequence that the ethanol cost will be higher, while the electricity cost will be lower than the real cost.

Figure 7 shows the dependence of the unitary economic cost for electricity and hydrated ethanol calculated for a distillery with steam parameters of 8 MPa/510°C and a capacity of 480 tc/h.

This means that, when the market price of the ethanol grows, this can economically compensate the decrease in the commercialisation price of surplus electricity, a phenomenon known as internal cost allocation. To calculate the cost of the generated electricity, it is necessary to estimate in advance the hydrated ethanol production cost, as this is the main distillery product. The average unit cost calculated for hydrated ethanol in the different plant capacities was 0.18 USD$/l. Electricity production costs for all the evaluated scenarios starting from this average ethanol cost are presented in Figure 8.

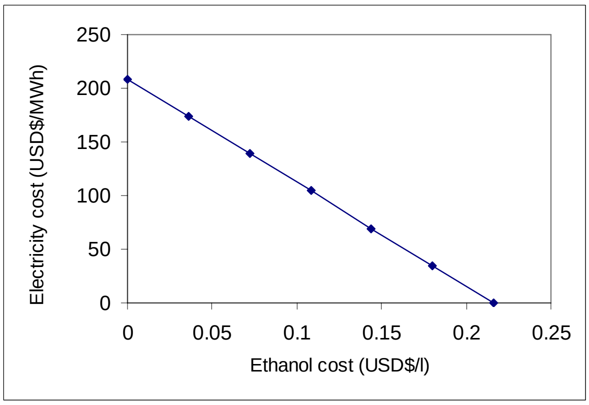

Fig. 7—Monetary unit cost of ethanol and electricity.

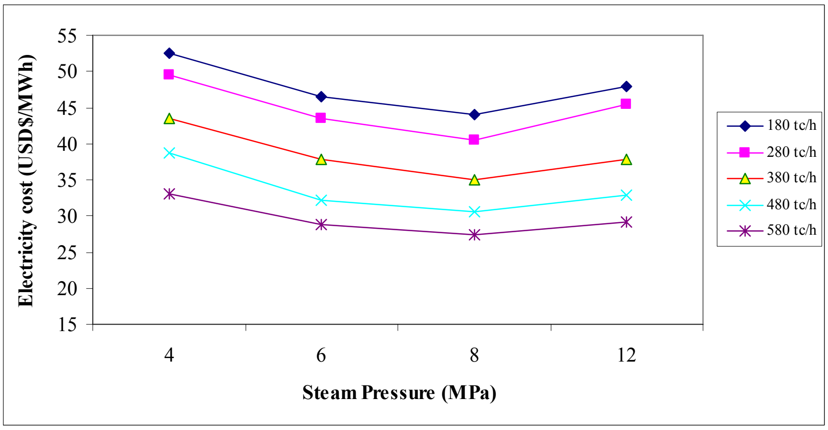

Fig. 8—Electricity cost for different steam parameters and distillery capacities.

Figure 8 shows that the highest values of electricity cost production are obtained for steam parameters of 4.2 MPa/420°C with values of 52.60, 49.56, 43.53, 38.74 and 33.03 USD$/MWh for each one of the considered plant capacities.

However, it's possible to obtain a reduction of these values by approximately 13% through the increase in the steam parameters from 4.2 MPa up to 6 MPa, and a reduction of 6% by the implementation of steam parameters of 8MPa instead of 6.0 MPa.

When the steam parameters are increased from 8 up to 12 MPa, the electricity generation cost increases by approximately 8%, due to the higher investment in some plant components. In this case, the boiler cost increases approximately 31%.

When steam parameters are increased from 4.2 up to 6 MPa, the boiler costs increase by 22% and, in the case when passing from 6 up to 8 MPa, this cost increases is 9%, approximately.

It is observed in Figure 8 that, from an economic point of view, the steam parameters of 12 MPa do not represent significant advantages for the electricity cost generation, different from the results obtained when using only the thermodynamic analysis.

Finally, as a complement of the obtained results, cash flow analyses were performed for the determination of the economic attractiveness of the considered scenarios. The Net Present Value (NPV) was used as an economic feasibility indicator. For calculation, an IRR of 15% was assumed representing the minimum attractivity rate, a value assumed by investors based on market conditions. With the increase in the IRR value, the economic attractiveness of some of the evaluated scenarios could be reduced, especially the ones, shown in Figure 10, with lower ethanol market prices.

Taxes and discount rates adopted for this work during cash flow analysis are presented in the Table 3.

Table 3—Economic environment indicators.

Indicator	Value	Unit
Electricity sale price	56.57	USD$/MWh
Hydrated ethanol sale price	0.17–0.30	USD$/l
Industrial electricity price – buying	98.6	USD$/MWh
Brazilian taxes ICMS, IPI, PIS, COFINS	18	%
Brazilian taxes IRPJ / CSLL	35	%
Planning time horizon	20	years
Financed fraction of the investment	40	%
Financing system	Price	
Interest rate	8	%
Internal rate of return (IRR)	15	%

ICMS: Value-Added Tax (V.A.T.) on Sales and Services
IPI – Excise Tax
PIS – Social Integration Program Tax
COFINS – Social Security Financing Contribution
IRPJ – Company Income Tax

Figure 9 shows the main NPV obtained in the different evaluated scenarios. It is observed that, for fixed market prices of ethanol and electricity of 0.30 USD$/l and 56.56 USD$/MWh, the attractiveness of the investment increases when the steam parameters go from 4.2 up to 8 MPa and the plant capacity is in the range of 380–580 tc/h.

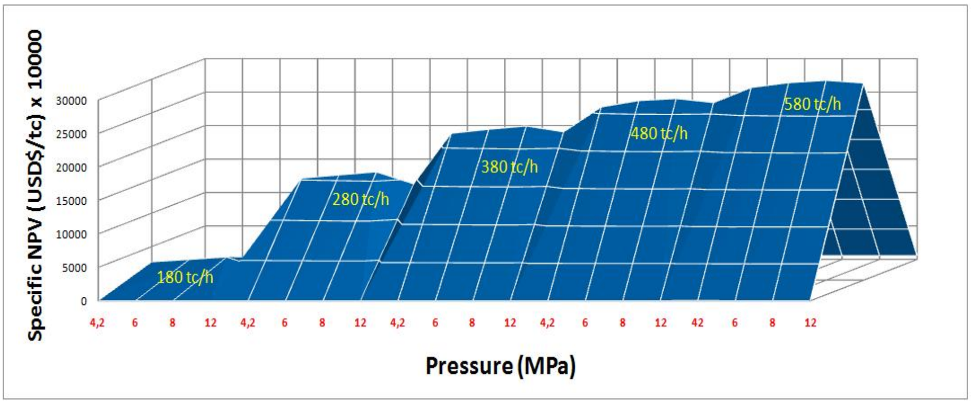

Fig. 9—Specific Net Present Value for a distillery as a function of steam parameters and plant capacity for ethanol and electricity market prices of 0.30 USD$/l and 56.57 USD$/MWh respectively.

In spite of allowing a higher global efficiency of the plant, the steam parameters of 12 MPa present a lower economic attractiveness than the steam parameters of 8 MPa, which need a lower initial investment.

In the cash flow analyses, another scenario was considered with ethanol and electricity prices of 0.17 USD$/l and 56.57 USD$/MWh. Main results are shows in Figure 10. As shown, the economic feasibility of autonomous distilleries in the range of 180 – 280 tc/h presents high dependence from the ethanol market price. This is not valid for distilleries in the range of 380 up to 580 tc/h with steam parameters of 8 MPa. It's observed that the increase in the steam parameters for maximising the electricity surplus and choice of the plant capacity are main factors for assuring the economic feasibility of ethanol plants when the market price of ethanol and electricity is variable.

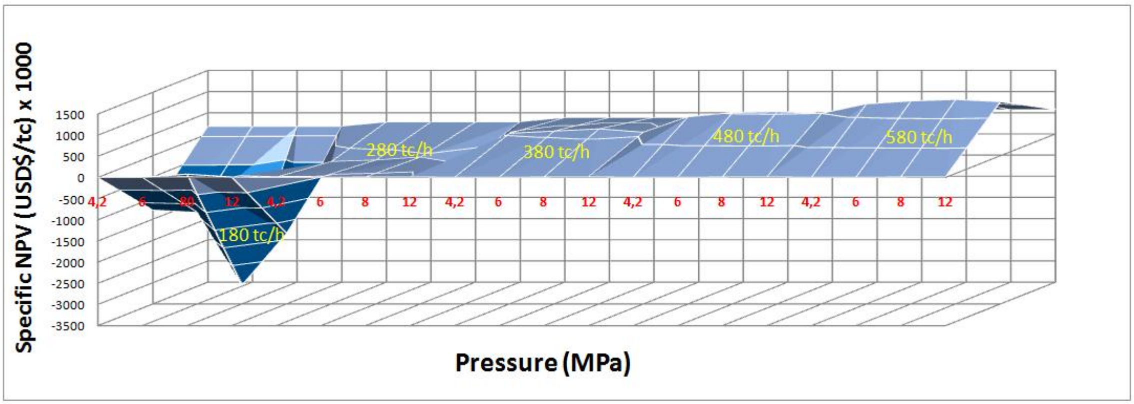

Fig. 10—Specific Net Present Value for a distillery as a function of steam parameters and plant capacity for ethanol and electricity market prices of 0.17 USD$/l and 56.57 USD$/MWh respectively.

Conclusions

The market price of electricity can compensate possible oscillations in ethanol market prices, so the internal cost allocation gives certain flexibility in reaching economic feasibility during autonomous distillery investment planning and operation.

Actually, the steam parameter that allows obtaining the lowest electricity generation cost is 8 MPa, in spite of steam parameters of 12 MPa resulting in higher plant global efficiency.

The economic feasibility of autonomous distilleries is strongly dependent on the steam parameters adopted for the cogeneration plant, mill capacity and market prices of ethanol and electricity. The increase in the plant capacity enables a higher economic attractiveness.

Thermo-economics, through exergy flows evaluation, is a powerful tool for cost allocation in autonomous distilleries, allowing to obtain final product cost that reflects the process of cost formation in the plant.

Acknowledgements

The authors would like to acknowledge the Brazilian equipment manufacturers Dedini Industrias de Base S.A, Texas Turbines, Equipalcool, HPB/Sermatec, NG Metalurgica and TGM for supplying process and cost equipment data.

The authors acknowledge also the funding agencies CAPES, CNPq and FAPEMIG for the financial support for this study through Ph.D and research productivity grants

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UNE MISE À JOUR DE L'EFFICACITÉ DE COGÉNÉRATION ET INDICATEURS ÉCONOMIQUES À L'AIDE DE TECHNOLOGIES COMMERCIALES MODERNES

Par

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MOTS-CLES: Éthanol, Cogénération, Coût de Production.

Résumé

UN SCENARIO tenant compte des capacités, des paramètres et des prix de commercialisation des équipements pour des systèmes de cogénération a été effectué; des différents coûts de fabrication de source brésilienne ont été examinés et les données y relatives sont présentées par le biais de tableaux et des graphiques. A l'aide du logiciel Gate-Cycle des unités de cogénération ont été modélisées pour des distilleries d'éthanol de capacités différentes. Utilisant les balances énergétiques et les données sur les coûts des équipements, le coût de la production d'électricité a été calculé pour chacun des scénarios évalués. A la lumière des résultats des scénarios évalués, les indicateurs tels que: indice de surplus d'électricité, facteur de l'utilisation d'énergie et l'efficacité énergétique sont présentés. Les recommandations issues des scénarios les plus rentables sont présentées tenant compte des prix actuels de commercialisation de l'électricité d'environ 56.52 $ US/MWh et deux niveaux de prix d'éthanol: 0.30 et USD 0.17 $ / l.

UNA ACTUALIZACIÓN DE LA EFICIENCIA DE LA COGENERACIÓN Y LOS INDICADORES ECONÓMICOS, EMPLEANDO TECNOLOGÍAS COMERCIALES MODERNAS

Por

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PALABRAS CLAVE: Etanol, Cogeneración, Costo de Pr oducción.

Resumen

SE ELABORÓ un escenario considerando capacidades, parámetros y precios de comercialización para equipos de sistemas de cogeneración , se consideraron diferentes costos de manufactura brasileñas y datos realcionados presentados en tablas y figuras. Empleando el software 'Gate-Cycle' se modelaron esquemas de plantas de cogeneración para diferentes capacidades de destilación de etanol. Se calculó el costo de generación de electricidad para cada escenario evaluado empleando datos de balances de energía y costos de equipos. Como resultado de la evaluación de los escenarios se presentan indicadores como el índice de energía sobrante, el factor de utilización de enrgía y al eficiencia energética. Se ofrecen recomendaciones acerca de los escenarios más rentables , considerando los actuales precios de comercialización de electricidad en el entorno de 56.53 US$/MWh y los precios del mercado de etanol: 0.30 y o,17 US$/L