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ENERGETIC AND ECONOMIC EVALUATION OF WASTE GLYCEROL COGENERATION IN BRAZIL

J. Q. Albarelli[1*], D. T. Santos[2] and M. R. Holanda[3]

[1]School of Chemical Engineering, University of Campinas, (UNICAMP), Phone: + (55) (19) 3521-3900, Fax: + (55) (19) 3521-3910, Cidade Universitária Zeferino Vaz, C. P. 6066, CEP: 13083-970, Campinas - SP, Brazil.
E-mail: jualbarelli@yahoo.com.br
[2] Faculty of Food Engineering, University of Campinas, (UNICAMP), Cidade Universitária Zeferino Vaz, C. P. 6121, CEP: 13083-862, Campinas - SP, Brazil.
[3] Engineering School of Lorena, University of São Paulo, (USP), Estrada Municipal do Campinho, C. P. 116, CEP: 12602-810, Lorena - SP, Brazil.

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Abstract - Glycerol is an important by-product of biodiesel production. It is used in many industrial segments, but the increasing production of this chemical has become an issue of concern. Many studies have been done to give new applicability to this product; a promising field is the usage of glycerol for energy production. Therefore, this study evaluates the technical and economic feasibility of a new and potential proposal at the national level, the generation of electricity and heat, through a cogeneration system using glycerol. The results demonstrate the viability of this proposal, since the payback on capital invested obtained was approximately 4 years, with the possibility of reduction to 3 years when installed in regions with low infrastructure.
Keywords: Glycerol; Cogeneration; Energetic and economic analysis; Brazil.

INTRODUCTION

The pursuit for alternative combustibles is a goal for many nations. Brazil is known as a renewable combustibles producer using biomass to produce biofuels such as ethanol and biodiesel. The generation of energy from vegetable oils has been strongly encouraged by the government. It can promote a decentralized energy production, giving opportunities to small producers (family agriculture) and generating funds in small communities in different country areas, offering alternatives to solve difficult economic and socio-environmental problems. In this context, a National Program for the Production and Use of Biodiesel (PNPB) was established in Brazil in December of 2004 (Garcez and Vianna, 2009) aiming at the substitution of a fraction of the fossil diesel used in the country by biodiesel within the next years.

Glycerol is an important by-product of biodiesel production. This compound is commonly used in different industry segments such as chemical, food and pharmaceutical. The average demand for this compound in Brazil is around 13 thousand tons per year (ABIQUIM, 2005). But, to meet the Brazilian government policies of incorporating 5% biodiesel in conventional diesel, it is estimated that around 2.6 billion liters of biodiesel will be produced per year (MME, 2011) resulting in the production of around 300 thousand tons of glycerol per year (MME, 2007; Biodiesel, 2007a). Therefore, it is expected that a great amount of surplus glycerol will be available on the market. This new situation needs to be fully investigated and new uses for glycerol proposed, otherwise there is a chance that glycerol will have to be disposed of as waste.

Several alternatives have been studied to convert glycerol from biodiesel production into different products by chemical and/or biochemical processing. Energy production from glycerol is a very promising field for investigation due to its nontoxicity, extremely low vapour pressure, low flammability and high energy density characteristics (Arechederra and Minteer, 2009). Recent studies show the

*To whom correspondence should be addressed

possibility of utilization of crude glycerol for syngas production through steam reforming (Dou *et al*., 2008, Adhikari *et al*., 2008), hydrogen production through fermentation (Sabourin-Provost and Hallenbeck, 2009) and energy production through fuel cells and biofuel cells (Ragsdale and Ashfield, 2008, Arechederra and Minteer, 2009). Among many technologies for energy production from raw materials like biomass, the steam cycle is one of the most used in Brazil. Lora and Andrade (2009) concluded that this process presents high technological maturity and economic feasibility in Brazil.

The use of glycerol as a fuel for electricity and heat production in a cogeneration system operating in a steam cycle could be an alternative to fulfill the energetic requirements of a biodiesel production process. The present study evaluates, through an energetic and economic analysis, the use of glycerol in a cogeneration system that generates heat and electricity to supply the energetic demand of the biodiesel production plant.

MATERIALS AND METHODS

Cogeneration System

The cogeneration system studied operates as steam cycle-based, with a conventional steam generator adapted for burning glycerol; a back-pressure steam turbine connects the steam generator to the industrial process, supplying saturated steam at 0.7 MPa and producing electricity (Figure 1). The technology for burning glycerol in a steam generator is not fully developed; therefore, it was assumed in this study that the burning system would be effectively modified so that glycerol would be burn with 85% efficiency in the steam generator.

Due to the aggressive nature of some fume gases, such as hydrochloric acid and others, it was established that the temperature of the steam as it leaves the steam boiler is 400ºC, to prevent corrosion (Otoma *et al*., 1997, Korobitsyn *et al*., 1999). An accurate control of the burning system is necessary so that incomplete combustion of glycerol does not cause the formation of acrolein. According with Bonnardeaux (2006), acrolein formation occurs only when the burning of glycerol is conducted at temperatures lower than 400ºC, this situation was not considered in this study.

Determination of the Input Flow of Glycerol and Characteristics

The low heating value (LHV) considered in this analysis was 14,300 kJ / kg. The flow of glycerol used was 0.36 kg/s, based on the data of glycerol production, 9.2 thousand tons per year, of the company Granola Ltda. (Biodiesel, 2007b).

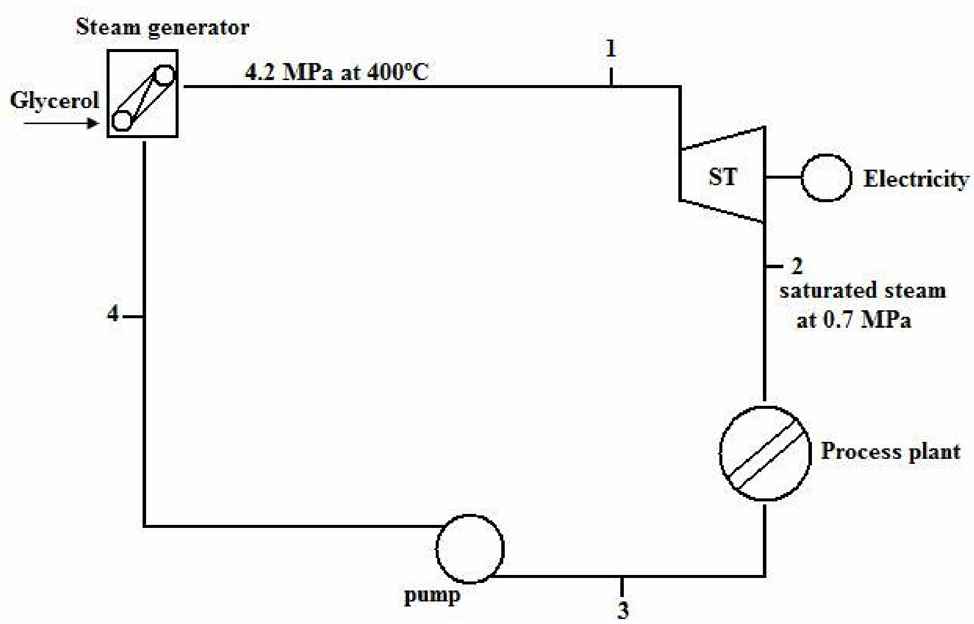

Figure 1: Steam cycle with a conventional steam generator and a back-pressure steam turbine.

Modeling

The cogeneration system will be used to supply energy for the biodiesel production plant. In accordance with the glycerol output adopted, the electricity consumption of the biodiesel production plant should be 2.49 x 10^6 kWh/year (Vecchio, 2006). It was assumed that the steam produced will supply all of the heat demand of the production plant.

The energetic analysis was conducted using the modeling proposed by Albarelli *et al*. (2007). The following equations were used to calculate the main parameters; the equipment efficiencies were assumed to be 85% for the steam generator, 95% for the electric generator and 80% for the pump. The input data for thermal analysis can be seen in Table 1.

Table 1: Input data for thermodynamic analysis.

State	Pressure (MPa)	Temperature (ºC)	Enthalpy (kJ/kg)
1	4.2	400	3210
2	0.7	175	2787
3	0.25	125	525
4	4.4	125.5	530

Steam flow:

$$\dot{m}_s = \frac{0,85 \times m_{glycerol} \times LHV_{glycerol}}{\left(h_1 - h_4\right)} \tag{1}$$

Glycerol energy content:

$$\dot{E}_{glycerol} = \dot{m}_{glycerol} \times LHV_{glycerol} \tag{2}$$

Axis power generated:

$$\dot{W}_e = \dot{m}_s \times \left(h_1 - h_2\right) \tag{3}$$

Electric energy generation:

$$\dot{E}_p = 0,95 \times \dot{W}_e \tag{4}$$

Thermal energy generation:

$$\dot{E}_C = \dot{m}_s \times \left(h_2 - h_3\right) \tag{5}$$

Pump consumed power:

$$\dot{W}_{pump} = \frac{\dot{m}_s \times \left(h_4 - h_3\right)}{0,80} \tag{6}$$

Electric efficiency:

$$\eta_{ge} = \left(\frac{\dot{E}_p - \dot{W}_{pump}}{\dot{E}_{glycerol}}\right) x100 \tag{7}$$

Thermal efficiency:

$$\eta_{gc} = \left(\frac{\dot{E}_C}{\dot{E}_{glycerol}}\right) x100 \tag{8}$$

Combined electric and thermal efficiency:

$$\eta_{global} = \left(\frac{\dot{E}_p + \dot{E}_C}{\dot{E}_{glycerol}}\right) x100 \tag{9}$$

An economic analysis was undertaken to evaluate the pay-back period (k) obtained for the proposed scheme. Table 2 shows the parameters used in the economic analysis. The following equations were used for the economic evaluation:

Table 2: Input data for economic analysis.

Electric consumption of the biodiesel production plant[1]	2.492.000	kWh/year
Electricity cost (purchase)[2]	0.07	US$/kWh
Electricity cost (sell)[2]	0.04	US$/kWh
Disposal cost for glycerol incineration[3]	0.015	US$/kg
Operation time of the cogeneration system	7200	h/year
Maintenance costs of the steam cycle[2]	0.008	US$/kWh
Maintenance costs of the complete steam cycle[2]	0.017	US$/kWh
Investment cost for the complete steam cycle[2]	4500	US$/kW

[1] Data obtained from Vecchio (2006).
[2] Data obtained from Albarelli *et al*. (2007). Maintenance and investment costs data of a municipal solid-waste cogeneration system.
[3] Estimated price paid for glycerol disposal in an incineration facility.

1) Annual electrical benefit for the installation of cogeneration:

$$B_{el} = \left(\dot{E}_P \times FS - Er\right) \times C_{els} + Er \times C_{elb} \tag{10}$$

2) Annual thermal benefit for the installation of cogeneration:

$$E_s = \dot{m}_S . \left(h_1 - h_4\right) \tag{11}$$

$$\eta_{SG} = \frac{E_s}{\dot{E}_{glycerol}} = 0,85 \tag{12}$$

$$C_{glycerol} = \frac{\left(\$_{glycerol} \times \dot{m}_{glycerol} \times \frac{1}{FS}\right)}{\dot{E}_{glycerol}} \tag{13}$$

$$CV_{SG} = \frac{\left(C_{glycerol} \times \dot{E}_{glycerol}\right)}{E_s} + CM_{SG} \tag{14}$$

$$B_{Th} = CV_{SG} \times E_{s,an} \tag{15}$$

3) Annual benefit for the installation of cogeneration:

$$B = B_{el} + B_{Th} \tag{16}$$

4) Annual income expected:

$$I = B - \left(CM_{STS} \times \dot{E}_P \times FS\right) \tag{17}$$

5) Pay-back calculation:

$$k = \left(\frac{C_{inv,sts}}{I}\right) \tag{18}$$

Energetic and economic analyses were performed with the help of the software LINGO 7.0 (Lindo Systems, 2011).

RESULTS AND DISCUSSION

An energetic analysis was performed to evaluate the possibility of using glycerol in a cogeneration system. The results can be seen in Table 3.

The global efficiency obtained was around 85%, demonstrating the high efficiency of this cycle. More thermal energy ($\dot{E}_c$) was produced than electricity ($\dot{E}_P$) due to the fact that the steam cycle operates chiefly to attend the thermal demand. Nonetheless, analyzing the total energy produced by this system in one year, considering 24 h of work per day and 300 days of work per year, the total electricity produced is 4.9 x 10^6 kW.h/year. The needs of the biodiesel production plant can be fulfilled by 50% of the total amount of electricity produced. The other 50% of surplus electricity can be sold to the local concessionary or to the local community.

The results obtained for the economic analysis of this cycle can be seen in Table 4. The pay-back of around 4 years found in this analysis is considered to be moderate for an investment in infrastructure.

Depending on the biodiesel production process the crude glycerol characteristics, such as water content and contaminants, can vary; therefore, the energy density of the glycerol can also vary. A process which diminishes the water content on the crude glycerol would provide a higher heating value to the glycerol. In this situation, the electricity production would certainly increase, as more steam could be generated. With higher electricity production, more surplus electricity can be sold to the local concessionary, increasing the income of the cogeneration facility and, therefore, reducing the payback time.

Table 3: Energetic analysis results.

$\dot{m}_{glycerol}$ (kg/s)	$\dot{m}_v$ (kg/s)	$\dot{E}_{glycerol}$ (kW)	$\dot{W}_e$ (kW)	$\dot{E}_p$ (kW)	$\dot{E}_c$ (kW)	$\dot{W}_{pump}$ (kW)	η_{ge} (%)	η_{gc} (%)	η_{global} (%)
0.36	1.63	5148.00	690.66	656.13	3693.31	10.20	12.55	71.74	84.49

Table 4: Economic analysis results.

$\dot{m}_{glycerol}$ (kg/s)	$\dot{E}_p$ (kW)	Investment cost (US$)	K (years)
0.36	656.13	2.952.585	4.23

Biodiesel production in Brazil is constantly increasing. This field has been attracting investments of big national companies like Vale and Petrobras and those of many other smaller companies are growing. In the future, companies with higher biodiesel production capacity will possibly be installed and a greater amount of glycerol will be generated in the production process, increasing the flow used in the cogeneration system. Based on this scenario, the increase in glycerol flow used in cogeneration was analyzed (Figure 2). With the increase in the glycerol flow, the pay-back suffers a minor increase. Even with a flow four times higher than the original one proposed, the pay-back time goes only from 4.2 years to 4.6 years. The higher flow analyzed in this study is still hypothetical since it represents 2.6 times the installed capacity of one of the main Brazilian biodiesel companies (140 million liters of biodiesel per year) (Biodiesel, 2007a; UDOP, 2011).

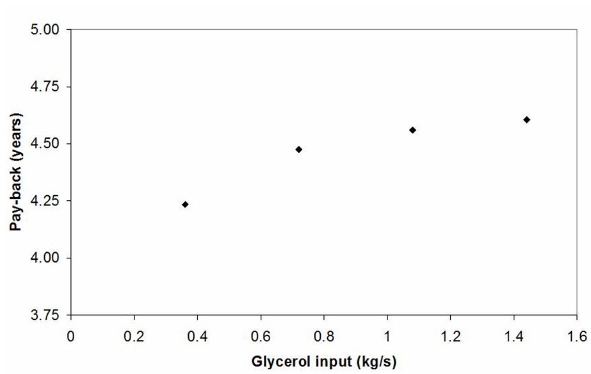

Figure 2: Pay-back variation considering different glycerol input flows.

The increase in the pay-back time might seem to be a counter-intuitive result; however, it occurs because the increase in the biodiesel production induces not only a higher glycerol flow, but also a higher energy consumption. Also, the increase in glycerol availability increases the investment in the cogeneration facility. The electricity generated by the extra amount of glycerol produced is proportional to the increase in electricity consumption at the biodiesel production and, therefore, little increase is noted in the surplus electricity sold to the local concessionary. Therefore, the income increases in a smaller proportion than the increase in the investment cost, so by Equation 18 the pay-back time increases.

A different scenario, which could result in a decrease of the pay-back time, would be if the electricity consumption by the biodiesel production process did not increase proportionally to the glycerol flow. This could be achieved by using more energy efficient equipment and thermal integration of the biodiesel production process. This could be performed before installation of a new biodiesel plant with higher capacity or during the substitution of equipment and adaptation of the existing process to increase the biodiesel production.

Some of the costs such as electricity price and disposal costs can vary depending on the location of the investment in the country. Figure 3 shows the effect of these parameters on the pay-back time. Cities such as São Paulo, which have many industries and much infrastructure, present low energy and disposal costs. On the other hand, in some regions electricity can be up to 50% more expensive (DIEES, 2009) than in São Paulo, in addition to high transport fees and few alternatives to glycerol usage that make disposal costs higher.

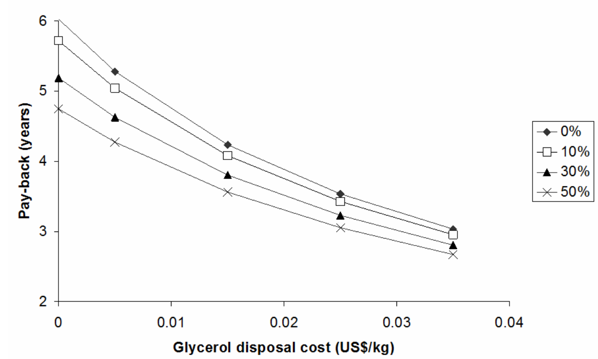

Figure 3: Pay-back variation considering different glycerol disposal costs and an elevation of 10%, 30% and 50% in the energy price.

It can be seen in Figure 3 that, with higher electricity and disposal costs, the pay-back time is shorter. Thus, the most attractive places to install this cogeneration system are those with less infrastructure, and thus higher energy and disposal costs, like many agricultural areas in the North, Northeast and Semi-arid regions of the country. Figure 4 presents a map of Brazil, in order to visualize its five large regions (North, Northeast, Central-West, Southeast, and South). These results are in agreement with the Brazilian Biodiesel Production Program, which incentivates decentralized biodiesel production to stimulate regional development. The government incentives culminated in a distribution of the biodiesel production of 35% in the central-west, 20% in the Northeast and 5% in the North (Garcez and Vianna, 2009).

Figure 4: Brazil's 5 large regions are comprised as follows: Northeast (MA, PI, CE, RN, PB, PE, AL, SE, BA); Southeast (ES, MG, RJ, SP); South (PR, SC, RS); North (RO, AC, AM, RR, PA, AP, TO); and Central-West (MT, MS, GO, DF). (Garcez and Vianna, 2009)

Considering the installation of the biodiesel production facility in a low infrastructure area, the possibility exists that, at first, the surplus electricity generated cannot be sold to the local concessionary or community due to a lack of infrastructure. This scenario was analyzed for the disposal cost of 0.035 US$/kg. The pay-back time was 3.3, 3.2 and 3.1 years for a 10%, 30% and 50% increase in the energy price. Comparing this data to the pay-back found for a disposal cost of 0.035 US$/kg in Figure 3, the increase in the pay-back time was around 14% for the three cases, reflecting the small impact of the selling of energy in remote regions.

CONCLUSIONS

The utilization of glycerol from biodiesel production as a fuel is shown to be an attractive alternative. The energetic analysis showed that a steam cycle feed by glycerol can provide enough energy to supply the biodiesel production facility with heat and electricity. The pay-back time of this investment was considered to be moderate, but, depending on the location and size of the power plant, this can be diminished. The implementation of this project in isolated regions with low infrastructure can be a cost-effective alternative for biodiesel industries installed in those areas and for the development of the region. It was concluded that electricity and heat production from glycerol is viable, but more studies on the environmental impacts of this activity and burning conditions of this product are necessary.

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NOMENCLATURE

B	economic benefit
B_{el}	electric economic benefit
B_{th}	thermal economic benefit

C_{elb}	electricity cost (purchase)	
C_{els}	electricity cost (sell)	
$C_{glycerol}$	glycerol cost	
$C_{inv,sts}$	investment cost for the complete steam cycle	
CM	maintenance cost	
CV	steam cost	
$\dot{E}_C$	thermal energy produced in the cogeneration system and consumed by the process plant	
$\dot{E}_{glycerol}$	glycerol power content	
$\dot{E}_p$	electric power produced in the cogeneration system	
Er	electricity consumption of the biodiesel production plant	
E_s	steam power produced in the cogeneration system	
FS	operation time of the cogeneration system	h/year
h_i	ideal enthalpy at point i	
I	annual income expected	
k	pay-back period	
$\dot{m}_i$	mass flow of stream i	
$\dot{W}_e$	axis power generated	
$\dot{W}_{pump}$	power consumed by the pumps	
η_{gc}	thermal efficiency	
η_{ge}	electric efficiency	
η_{global}	combined electric and thermal efficiency	
η_{SG}	steam generator efficiency	
$\$_{glycerol}$	disposal cost for glycerol incineration	

Subscripts

s	steam
SG	steam generator
an	annual
STS	steam cycle

Abbreviations

LHV	lower heating value

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