

ENCIT-2018-0163

COGENERATION SYSTEM APPLIED IN BIODIESEL PRODUCTION: ENERGY, EXERGY AND ECONOMICAL ANALYSIS

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Abstract. *In these days, the world is thinking about the greenhouse effect and what its need to do to decrease that. Scientists from all of the world has working hard doing researches about bioenergy and other ways to increase energetic efficiency and decrease the use of fossil fuels, reducing pollutant emissions. Biodiesel comes in that way because it's a fuel produced by vegetable oil or animal fat, that is to say, of renewable raw. One problem from biodiesel production is the co-product, the Glycerol. Brazilian market produces more glycerol than it can consume, so in this paper its studied one way to use that byproduct. Cogeneration is one technique used to generate two products from just one source of fuel. The purpose of this paper is to use natural gas into an internal combustion engine and generate electrical energy for the biodiesel process and saturated steam to use in the process of biohydrogen production by steam reforming of glycerol. Sankey and Grassman diagrams were constructed to visualize the energetic and exergetic flows. In final step, the economic analysis was applied based at the payback period method and the plant needs approximately two years to get the compensation, depending of the different annual interest rates.*

Keywords: *Cogeneration, Biodiesel, Exergy, Internal Combustion Engine, Combined Heat and Power.*

1. INTRODUCTION

The scientific community is committed to reduce the greenhouse gases released into the atmosphere through fossil fuels burning. Boloy *et al.* (2017) studies the possibility to apply hydrogen production in the biodiesel industry. One of the most promising methods to reduce greenhouse gases is decreasing the percentage of useful energy lost to the environment to increase the power plant efficiency and using alternative fuels such as biodiesel and biohydrogen.

Brazil has increased its biodiesel production over the years, however, its mills are not producing at maximum capacity. The country can increase the planted area with biodiesel feedstocks without interfering with pasture areas or areas used for feed crops. With governmental incentives, Brazil can become an even more important biodiesel producer. However, the ultimate challenge for the future is to make biodiesel that is cost competitive with petrodiesel (Bergmann *et al.*, 2013).

According to EPE (2017), the federal government of Brazil has created the Interministerial Executive Committee on Biodiesel (CEIB) and the Management Group (GG) to study some biodiesel policy. In December 2004 was launched the National Program for Use and Production of Biodiesel (PNPB) to introduce this biofuel in the national energetic matrix. In January 13th, 2005 was approved the law 11.097/2005 and the 2% biodiesel blended with petrodiesel (B2) started to be mandatory. Currently this mixture is B10 and the production capacity is estimated as 5.4 billion liters per year.

The glycerol is the main sub product of the biodiesel industry (approximately 10% of total volume), in other words, to produce 10 liters of biodiesel, 1 liter of glycerol is produced too. Studies are being developed to transform this glycerol in something useful, for example, to produce biohydrogen (Alvarado e Gracia, 2007; Sanchez e Comelli, 2014; Souza e Silveira, 2011).

Applying cogeneration into the biodiesel industry, the efficiency of the plant can be increased. According to Galarza *et al.* Galarza *et al.* (2015), the efficiency of the plant studied was increased from 23.19% to 69.62%.

Silveira *et al.* (2012) defines cogeneration as a simultaneous production of an electrical or mechanical energy and useful thermal energy from a single energy source, such as oil, coal, natural or liquefied gas, biomass, or solar.

Prime movers for combined heat and power (CHP) systems may include different kinds of reciprocating engines, diverse types of turbines and new technologies like fuel cells (RENAC - Renewables academy).

2. METHODOLOGY

The cogeneration system was proposed based in that one proposed by (Galarza *et al.*, 2015). It's a system to produce electrical and thermal energy to a biodiesel and biohydrogen plant.

The plant produces 8000 ton/year of biodiesel and have the glycerol as a sub product, working 8000 hours/year. The biodiesel is produced by a process called 'transesterification', and it's use canola's oil with methanol in presence of a catalyst.

The system was proposed to work in thermal parity working with natural gas. Fuel enters the system with air (PR = 15 and 30% excess air) (point 1) and the internal combustion engine generates electrical energy. The exhaust gases of the system (point 2) goes to a recovery boiler and after that to the environment (point 3). At the recovery boiler water is pumped from point 4 to point 5, changing its phase to saturated steam.

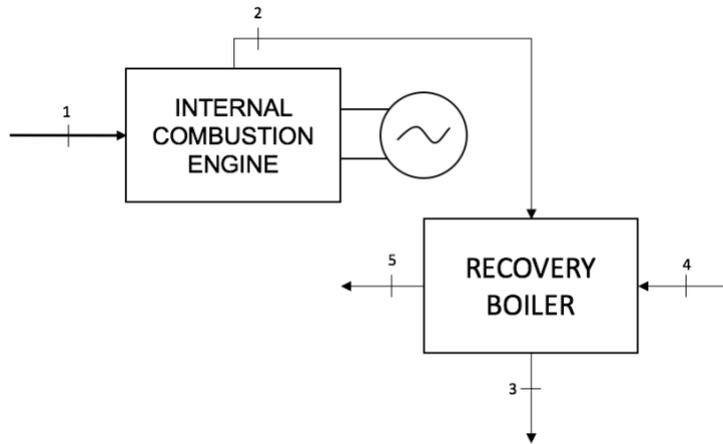


Figure 1. Cogeneration system proposed

2.1 Technical analisys

The fuel considered was the natural gas with LHV 35564 kJ/Nm³ (Yang *et al.*, 2015). Table 1 shows the temperatures, enthalpies (h) and entropies (s) of the system.

Technical analysis was performed according to the 1st and 2nd law of thermodynamics.

Table 1. Thermodynamics properties of the system

Point	Substance	Mass flow [kg/s]	Temperature [°C]	h [kJ/kg]	s [kJ/kg.K]
1	Natural gas	0,002798	25	-	-
2	Exhaust gases	0,057361	550	-	-
3	Exhaust gases	0,057361	155	-	-
4	Water	0,035278	90	377,1463	1,1925
5	Saturated steam	0,035278	133,5	2724,8917	6,9916

Heat exchange at the recovery boiler was calculated with the equation 1.

$$E_{HRSG} = \dot{m}_{steam} \cdot (h_4 - h_5) \quad (1)$$

Where:

E_{HRSG} - Heat change at the heat recovery steam generator [kW]

\dot{m}_{steam} - Steam flow [kg/s]

h_4 - Specific enthalpy at the point 4 [kJ/kg]

h_5 - Specific enthalpy at the point 5 [kJ/kg]

Table 2. Preliminary data of the ICE stream.

LHV _{ng}	35564	kJ/Nm ³	(Yang <i>et al.</i> , 2015)
cp _{gases}	1.15	kJ/kg.K	(Tuna, 1999)
η _{HRSG}	0,8	-	adopted
Air-fuel ratio	15	-	adopted
Excess air	30%	-	adopted

The Heat Recovery Steam Generator (HRSG) efficiency can be applied to determine the fuel energy, then with the equation 2 its calculated the fuel flow, in kilograms per second.

$$E_{fuel} = \dot{m}_{fuel} \cdot LHV_{ng} \quad (2)$$

Where:

E_{fuel} – Fuel energy [kW]

\dot{m}_{fuel} - Steam flow [kg/s]

LHV_{ng} – Low heat value of the natural gas [kJ/Nm³]

The air flow was determined as function of the fuel flow, air-fuel ration and the excess air. Adding these flows, it's found the exhaust gases flow. The energy generated by the internal combustion engine is calculated by the equation 3.

$$E_p = \dot{m}_{gases} \cdot cp_{gases} \cdot (T_2 - T_1) \quad (3)$$

Where:

E_p – Energy produced [kW]

\dot{m}_{gases} – Exhaust gases flow [kg/s]

cp_{gases} – Specific heat of the exhaust gases [kJ/kg.K]

Table 3. Energetic balance of the system.

Equipment	Energy [kW]
ICE	34,63
Power Generator	32,90
Recovery Boiler	45,41
Saturated Steam	82,82

The cooling air flow is unknown, so according to Valle *et al.* (2015), it was adopted a cooling energy lost about 21% from Ecomb. For a better visualization of the energy flow, a Sankey diagram was made and it's exposed in figure 2.

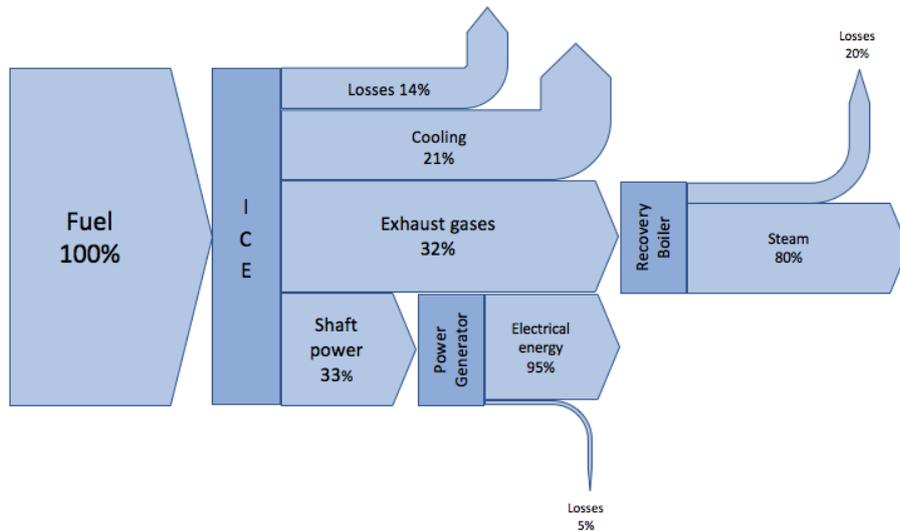


Figure 2. Sankey diagram.

For the exergetic analysis it's necessary the environmental properties. These data are shown at table 4.

Table 4. Properties of the air at the environment.

Environmental properties (air)	
Temperature	25 °C
Pressure	101,3 kPa
Enthalpy	298,6 kJ/kg
Entropy	5,695 kJ/kg.K

According to Tuna (1999), the fuel exergy is your own LHV. To calculate the exergies at the points 1, 2 and 3 it was used the equation 4 and for points 4 and 5, the equation 5.

$$\dot{E}x_{fuel} = \dot{m}_{fuel} \cdot LHV_{fuel} \quad (4)$$

Where:

$\dot{E}x_{fuel}$ – Fuel exergy [kW]

\dot{m}_{fuel} – Fuel flow rate[kg/s]

LHV_{fuel} – Fuel low heat value [kJ/Nm³]

$$\dot{E}x = \dot{m} \cdot c_p \cdot \left[(T_{gas} - T_0) - T_0 \cdot \ln \left(\frac{T_{gas}}{T_0} \right) \right] \quad (5)$$

Where:

$\dot{E}x$ – Exergetic flow [kW]

\dot{m} - Flow rate [kg/s]

c_p – Specific heat [kJ/kg.K]

T_{gas} – Temperature of the exhaust gases [°C]

T_0 – Temperature of the environment [°C]

Was also done the calculations for Bosnjakovic efficiency and the irreversibility's of the system.

$$\psi = \frac{\dot{E}x_{out}}{\dot{E}x_{in}} \quad (6)$$

$$I = \dot{E}x_{in} - \dot{E}x_{out} \quad (7)$$

Where:

$\dot{E}x_{in}$ – Exergy inlet [kW]

$\dot{E}x_{out}$ – Exergy out [kW]

I – Irreversibility's [kW]

ψ – Bonsjakovic efficiency [-]

These results are shown at table 5.

Table 5. Exergies results.

Equipment	$\dot{E}x_{in}$ [kW]	$\dot{E}x_{out}$ [kW]	ψ [-]	I [kW]
ICE	103.53	14.66	0.1416	88.87
Power Generator	14.66	13.93	0.9500	0.73
HRSG	14.66	1.46	0.0995	13.20
Saturated Steam	71.96	50.13	0.6966	21.83

The Grassman diagram have the same aim of the Sankey diagram, but for exergy. The figure 3 shows the exergies flow from the system.

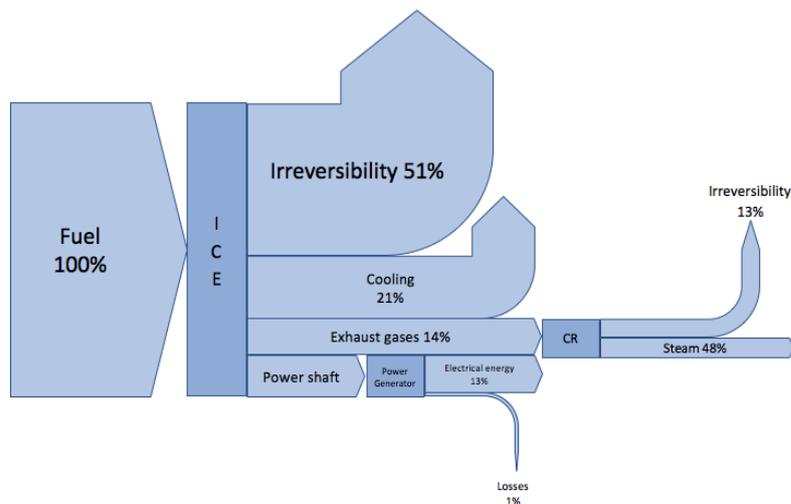


Figure 3. Grassman diagram.

2.2 Economical analisys

According to Silveira *et al.* (2012), for the economic analysis, it's used the payback method. Electricity production cost is the sum of investment in the plant, cost related to the fuel and the maintenance cost. This relation it's also applied for thermal energy and can be used to calculate the saturated steam cost. Equations 8 and 9 exposes it.

$$C_{electricity} = \frac{I_{ICE} \cdot f}{H \cdot E_p} + C_{fuel} \cdot \frac{E_{fuel} \cdot E_{ge} \cdot \frac{Losses}{2}}{E_p} + C_{main,ICE} \quad (8)$$

$$C_{steam} = \frac{I_{HRSG} \cdot f}{H \cdot E_{steam}} + C_{fuel} \cdot \frac{E_{ge} \cdot \frac{Losses}{4}}{E_{steam}} + C_{main,HRSG} \quad (9)$$

Where:

$C_{electricity}$ – Electricity cost [US\$/kWh]

C_{steam} – Steam cost [US\$/kWh]

C_{fuel} – Fuel cost [US\$/kWh]

$C_{main,ICE}$ – Maintenance cost of the internal combustion engine [US\$/kWh]
 $C_{main,HRSG}$ – Maintenance cost of the heat recovery steam generator [US\$/kWh]
 E_{ge} – Exhaust gases energy [kW]
 f – Annuity factor [year⁻¹]
 H – Period of use [hours/year]

Following the methodology of Boehm (Boehm, 1987), the investment cost of the internal combustion engine can be determined with the equation 10. Equation 11 determines the recovery boiler investment cost, according to Bruno (Bruno *et al.*, 1998).

$$I_{ICE} = 400 \cdot 10^3 \cdot \left(\frac{E_p}{455}\right)^{0.9021} \quad (10)$$

$$I_{HRSG} = 6996 + 211.5 \cdot \dot{m}_{steam} \quad (11)$$

Where:

I_{ICE} – Investment in the internal combustion engine [US\$]

I_{HRSG} – Investment in the heat recovery steam generator [US\$]

The maintenance costs of internal combustion engine and recovery boiler were obtained from equations 12 and 13, respectively (Ehyaei *et al.*, 2012; Silveira *et al.*, 2012).

$$C_{main,ICE} = 0.015 \quad (12)$$

$$C_{main,HRSG} = 0.1 \cdot \frac{I_{HRSG} \cdot f}{H \cdot E_{steam}} \quad (13)$$

In the economic point of view, is interesting to know the gain over the years. The gain is determined for each system separately. The sum of the gains is the annual expected revenue.

$$G_{electrical} = E_p \cdot H \cdot (T_{electricity} - C_{electricity}) \quad (14)$$

$$G_{thermal} = E_{steam} \cdot H \cdot (C_{steam,conv} - C_{steam,cogenerated}) \quad (15)$$

Which $C_{steam,conv}$ is obtained from equation 16.

$$C_{steam,conv} = \frac{P_{oil}}{\eta_{HRSG}} + C_{maintenance} \quad (16)$$

Where:

$G_{electrical}$ – Gain in electricity production [US\$/kWh]

$G_{thermal}$ – Gain in steam production [US\$/kWh]

$T_{electricity}$ – Electricity rate [US\$]

$C_{steam,conv}$ – Conventionally generated steam cost [US\$/kWh]

$C_{steam,cogenerated}$ – Co-generated steam cost [US\$/kWh]

$C_{maintenance}$ – Maintenance cost of the conventional steam generator [US\$/kWh]

P_{oil} – Oil price [US\$/kWh]

η_{HRSG} – Heat recovery steam generator efficiency [-]

These costs were plotted and they are shown in figure 4 and 5, respectively. The National Electric Energy Agency (ANEEL) is the agency responsible for regulating electricity tariffs in Brazil. On December/2017 this tariff for the industrial sector was at 0.3970 R\$/kWh and changing the money to dollars, with an exchange rate about 3.2582 on 03/06/2018, this tariff can be estimated as 0.1219 US\$/kWh (ANEEL, 2018).

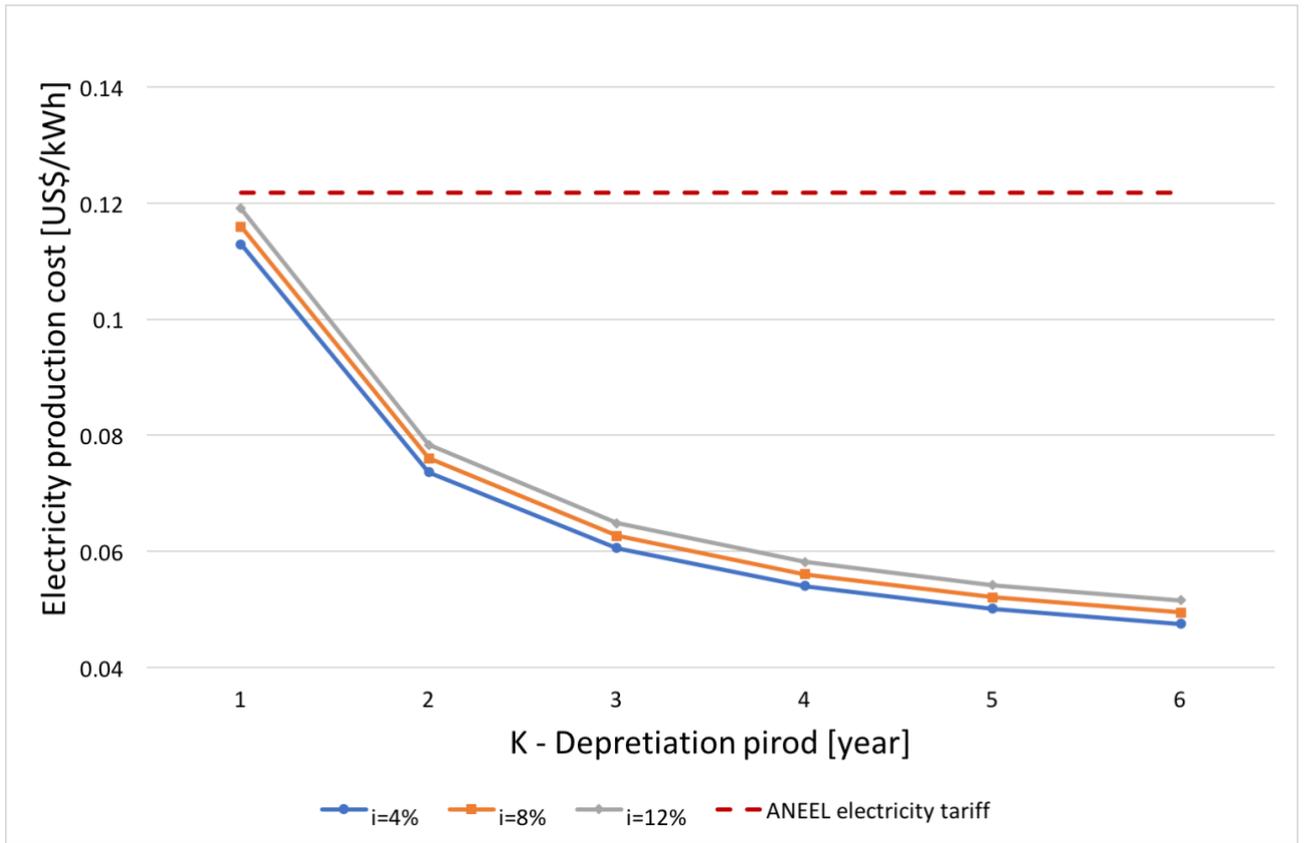


Figure 4. Electricity production cost.

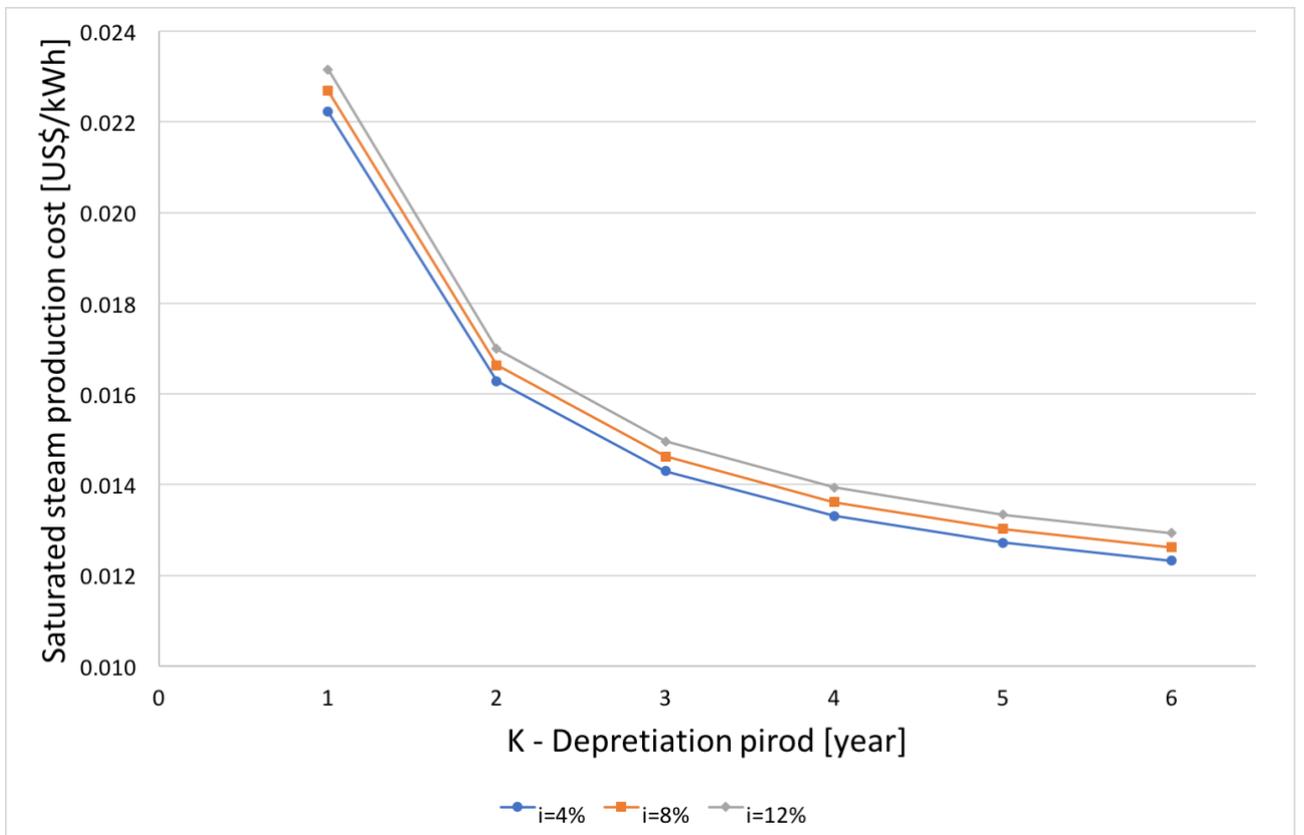


Figure 5. Saturated steam production cost.

Figures 6 show the annual expected revenue with 3 different annual bank interest rates.

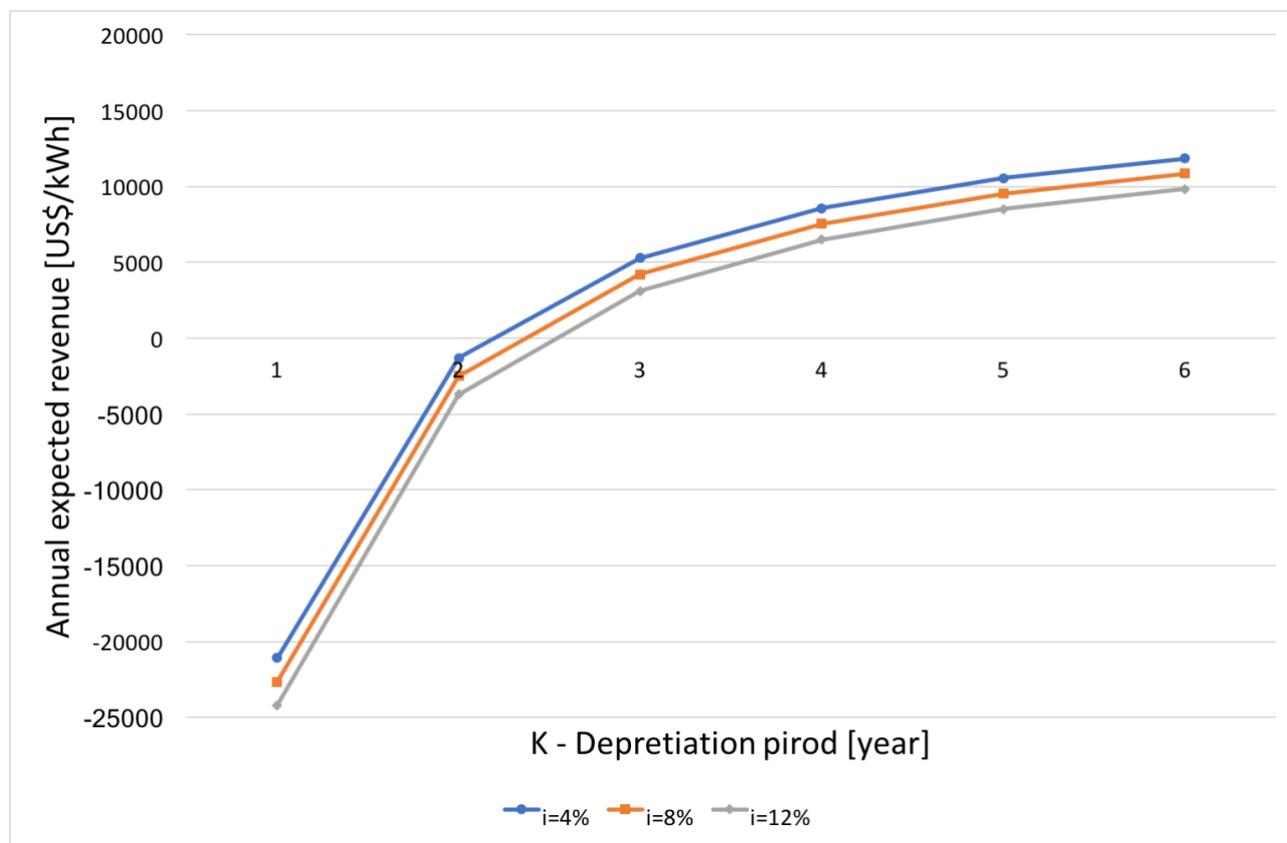


Figure 6. Annual expected revenue.

3. CONCLUSIONS

The biodiesel industry has developed and new technologies have been studied with actual applications.

In case of Brazil, the greater volume of glycerol has indicated some new trends for the production process. In this context, the steam reform of glycerol may contribute to the sector development, giving aggregate value to biohydrogen and reducing cost of biodiesel production.

New technologies considering the cogeneration techniques has been studied in all part of world, and have good applications with annual savings in biodiesel industry.

A cogeneration plant with an internal combustion engine and HRSG was proposed to generate electricity and saturated steam. These products should be used into an industry to produce biodiesel operating 8000 hours per year.

The process requires 10 kg/s of saturated steam at 0.3 MPa. From this require and other data shown in the tables 1 and 2, was calculated the electrical energy generated, 32.9 kW.

Analyzing the Sankey diagram, we have a visualization of the energetic flow from the proposed system. In the other hand, the Grassman diagram shows the irreversibility's of the system, which the major is at the internal combustion engine, around 51% of the fuel exergy.

At the cost graphs, it's easy to see the electrical cost is about 4.5 to 5 times greater than thermal cost.

Economically, the system proved feasible because have a payback period approximately in 2 years to 2 years and a half.

4. ACKNOWLEDGEMENTS

- CAPES by grant of Master's Scholarship;
- CNPq by the project of group;
- IPBEN-UNESP for providing the infrastructure for the studies.

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