# Studies on technical and economical viability of biodigesters associated to water reuse and energy cogeneration

## ESTUDOS EM VIABILIDADE TÉCNICA E ECONÔMICA DE BIODIGESTORES ASSOCIADA PARA MOLHAR USAM DE NOVO E COGERAÇÃO DE ENERGIA

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## ABSTRACT

This work evaluates technical and economical a miniETE (ministation of sewage treatment) by anaerobic-aerobic-anoxious process, associated to the utilization of biogas produced and utilization of treated effluent for fertilization and irrigation of green areas. The miniETE is modular, energy self-sufficient and constituted by the following systems: a) anaerobic, constituted by three sequential cascade anaerobic UASB digesters, with a helix shape phase separator system; b) aerobic-anoxious, constituted by a vertical cylindrical aerobic-anoxious biodigester operating with aeration of the fine bubble type; c) compact cogenerator, powered by biogas, capable of simultaneous production of electrical energy and hot water; d) effluent utilization for fertilization and irrigation, constituted by a distribution network The process aims the sanitation of sewage, utilization of produced biogas and of treated effluent, decreasing this way the environmental impact caused by the discharge without treatment of sewage in natural water courses and biogas into the atmosphere.

## KEYWORDS

Anaerobic-aerobic-anoxious treatment. Biogas utilization. Water reuse. Irrigation and Fertilization. Energy cogeneration.

## RESUMO

Este trabalho teve como objetivos, o desenvolvimento, a implantação e a avaliação técnica econômica e ambiental da implantação de miniETE (miniestações de tratamento de esgoto) associadas a sistemas de aproveitamento energético de biogás. A miniETE implantada é composta por: três biodigestores anaeróbios de fluxo ascende em manto de lodo, dispostos em série formando cascata, com sistema de separação de fases sólida-líquida-gasosa em formato helicoidal para tratamento do esgoto produzido por uma população de 1200 pessoas; um sistema de coleta, armazenamento e purificação de biogás; um biodigestor aeróbio-anóxio para pós tratamento do efluente tratado anaerobiamente; três sistemas compactos de cogeração de energia para o aproveitamento energético do biogás produzido nos biodigestores anaeróbios, sendo um primeiro composto por um motogerador de 5,5kW, um seguindo por um motor de corsa 1.000 acoplado a um gerador de 13 kW, e um terceiro composto por uma célula combustível de 5 W; e um sistema de ferti-irrigação de áreas verdes. Os resultados obtidos indicam que é técnica e economicamente possível conciliar saneamento com produção de energia alternativa, e dessa forma colaborar com a mitigação da eutrofização das águas, da proliferação de doenças hidrotransmissíveis e do descartes de metano na atmosfera.

## PALAVRAS CHAVE

Tratamento anaeróbio-aeróbio-anóxio. Uso do biogas. Reuso de água. Irrigação e ferti-irrigação. Cogeração de energia.

## Nomenclature

| | |
|---|---|
| Ereq | Electric power required by the ETE [kW] |
| Ipt | Total plant investment [US$] |
| B1 | pump 1 |
| k | Invested Capital amortization period [years] |
| B2 | pump 2 |
| Mb | Biogas consumption by TOTEM[$m^3/h$] |
| C1 | compressor 1 |
| R | Revenew [US$/yr] |
| Cet | Treated effluent cost [US$/$m^3$] |
| Pet | Cost of treated sewage [US$/ $m^3$] |
| CoETE | Treated sewage operational cost [US$/ $m^3$] |
| Ptl | Cost of transportation of exceeding sludge produced for $m^3$ [US$/$m^3$] |
| CmETE | ETE Maintenance cost [US$/$m^3$] |
| Qeb | Daily outflow of crude effluent [$m^3$/day] |
| DQO | Oxygen Chemical Demand [mg/l de OCD] |
| Pel | Price of acquired electricity [US$/kWh] |
| Ec | Recovered residual heat power [kW] |
| r | Return rate [%/yr] |
| Ecomb | Fuel power [kW] |
| RAFA | UASB Reactor |
| Ep | Electric Power produced by micro generator [kW] |
| Ta | Water temperature produced by cogenerator [°C] |
| H | Annual operating hours (h/yr) |
| TOTEM | Total Energy Module |
| ETE | Effluent Treatment Plant |
| UASB | Up-flow Anaerobic Digester in Sludge Bed |
| F | Annual factor [1/yr] |
| Vl | Volume of sludge exceedent [$m^3$/day] |

## Introduction

Contamination increase of our water courses, associated to a probable increase of energy cost, suggest anaerobic treatment as a viable alternative, by the utilization of materials considered expendable in the past. These materials, like food, human and animal residues, are possible substrates for the production of fuel biogas by anaerobic treatment.

In arid and semi-arid regions, water has become a limiting factor for urban, industrial and agricultural development. Planners and Water Resources Managing Organizations, are looking for new sources in order to improve water availability. Inferior quality water, such as used water, specially of domestic origin, water from agricultural draining and brackish water, whenever possible, should be considered as alternative sources for less restrictive uses. Appropriate technology for the development of these sources, together with the improvement of utilization efficiency and demand control, constitute today a basic strategy for the solution of the global shortage of water (HESPANHOl, 2000).

Les then 10% of Brazilian population has access to sewage treatment which is discarded in natural water bodies, causing eutrophization and dissemination of hidro-transmitted deseases (ALÉM SOBRINHO; TSUTIYA, 2000). In this same context, environment situation is aggravated, due to space restriction and evergrowing necessity to offer energy, good quality water and food. In the integrated anarobic-aerobic system, sewage is treated by UASB reactors, followed by aerobic after treatment. This process produce a residual sludge volume about 75% less of that produced by aerobic activated sludge, since a large portion of this sludge is transformed into biogas, which can be surely utilized in cogeneration systems, in order to decrease operational costs related to electric energy consumption [(VAN HAANDEL; LETTINGA,1994); (VON SPERLING, 1997); (GODOY JUNIOR, 2002)].

The development of efficient and low operational cost ETE plants, is a world necessity related to natural clean water and energy resources conservation.

In times of electrical energy shortage, this is an attractive alternative, since it conciliates sanitation with renewable energy. As a consequence of the problem of energy efficiency and the increase of water pollution, a very promising alternative and subject of many researches, starting now to be developed in full scale, is the anaerobic-aerobic-anoxious treatment of effluents, that is, anaerobic treatment , followed by aerobic treatment and treatment with nitrates (anoxious) for nutrients removal. In this case, the main advantages are: a) good quality drinkable water economy for human consumption, food and kitchenware cleaning, personal hygiene and food preparation and inferior quality water, not drinkable, for floors cleaning, irrigation and fertilization of green areas, toilet flush , among others; b) environment sanitation; c) energy utilization from biogas.

## Objectives of this Work

This work aims at the analysis of all aspects related to the economical and technical viability of developing ecologically correct techniques in the area of environmental management of domestic, commercial and industrial organic residual water.

Furthermore aims to the conception of a treatment system of easy construction and maintenance, together with low construction and operational costs.

## General Configuration of the Biodigester System Associated to Water Reuse and Energy Cogeneration

System configuration is shown in figure 1 (picture and flowchart), with emphasis to water, biogas and electric energy transportation used for the pumps and blowers of the miniETE.

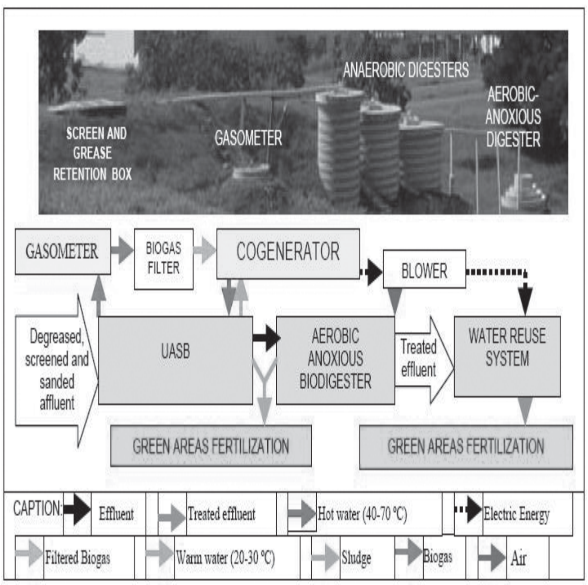


Figure 1- Photo and flowchart of water, biogas and electrical energy transportation in the miniETE

## MiniETE configuration

The miniETE was built basically using VPC thermoplastic pipes of diameters varying from 100mm to 2500mm.

## Optimized system of UASB digesters

The detailed description of effluent treatment process, in the Optimized System of UASB is given in figure 2: 1st) pre-treated effluent (degreased, screened and sanded) is distributed by means of a piping in the lower part of the sludge bed of the first biodigester, 2nd) as the effluent crosses the sludge bed (digestion zone), the anaerobic microorganisms in this sludge flocculent grains, digest the organic material of the effluent, producing very small bubbles of biogas at the sludge grains surface, increasing the upward force; 3rd ) Depending on the ascending speed of the effluent flow, the sludge bed expands and some of the gassed grains are dragged upward. 4th )in the separation zone between solid and liquid phases, by means of a helical shaped phase separator , the effluent is directed to the exit of the biodigester, the gassed grains are degassed in the phase separator, returning downward in the sludge bed and the biogas bubbles are directed to the collecting chamber. 5th ) afterwards, the effluent goes through the sludge bed and phase separator of the other biodigesters, sequentially.

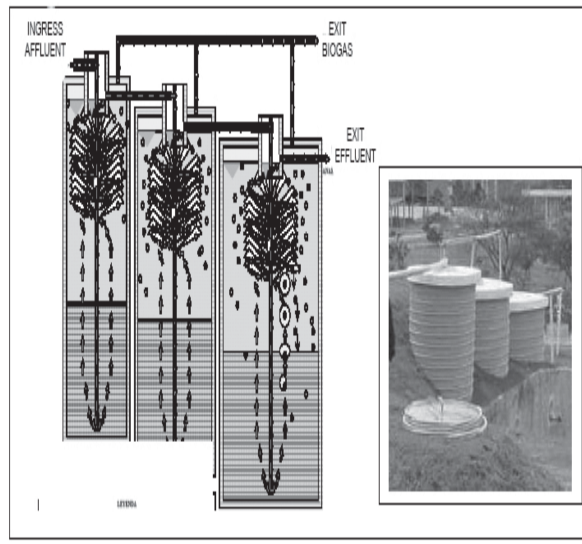


Figure 2 – Sketch of the optimized System of UASB and photo of the developed system

## Optimized system of the vertical cylindrical aerobic and anoxious digester system with aeration by fine bubbles

The detailed description of the effluent in the optimized system of aerobic and anoxious using cylindrical vertical biodigesters with aeration with fine bubbles, is shown in figure 3: 1st ) the anaerobic treated effluent is distributed in the upper part of the central cylinder in a descending flow crossing a aerobic sludge bed with fine air bubbles and by means of a aperture in the lower lateral part of the central cylinder, enters the lower part of the larger diameter cylinder, in ascending flow, crosses the aerobic sludge of this second cylinder and enter the setting zone; 2nd ) aerobic micro organisms in this sludge, digest the organic material still present after the anaerobic treatment, and promote the nitrification of ammonial nitrogen into nitrate; 3rd )afterwards the effluent is distributed in the upper part of a third cylinder with even larger diameter, crosses downward an anoxious sludge bed, enters the lower part of a fourth cylinder of even larger diameter, crosses upward the anoxious sludge bed of this fourth cylinder, goes through the setting zone and is directed outside the system; 4th )the anoxious micro organisms in the aerobic and anoxious sludge, decompose the nitrates in form of free nitrogen and eliminate part of the phosphor as a bacterian biomass of sludge.

## CONFIGURATION OF THE SYSTEM FOR STORAGE AND PURIFICATION OF BIOGAS AND ENERGY COGENERATION

Corresponding to the energetic utilization of biogas produced, three sequential systems were suggested. 1) biogas storage by a gasometer; 2) filtering of the sulphidric gas through an iron oxide filter; 3) energetic conversion of biogas into electric energy and hot water, through a compact cogenerator operating with biogas. Figure 4 shows the storage and biogas purification system called TOTEM. It is necessary proper construction granting a good yield and, as necessary, caustic isolation.

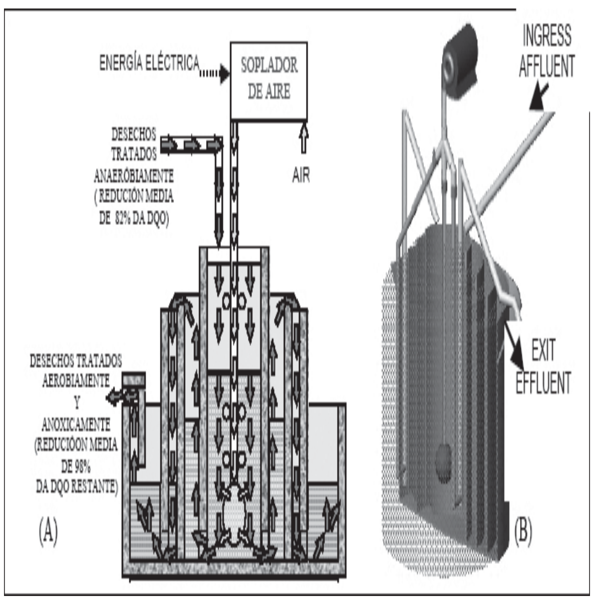


Figure 3 - Cross sectional sketch of the optimized system of aerobic and anoxious digester for post treatment of anaerobic treated effluent

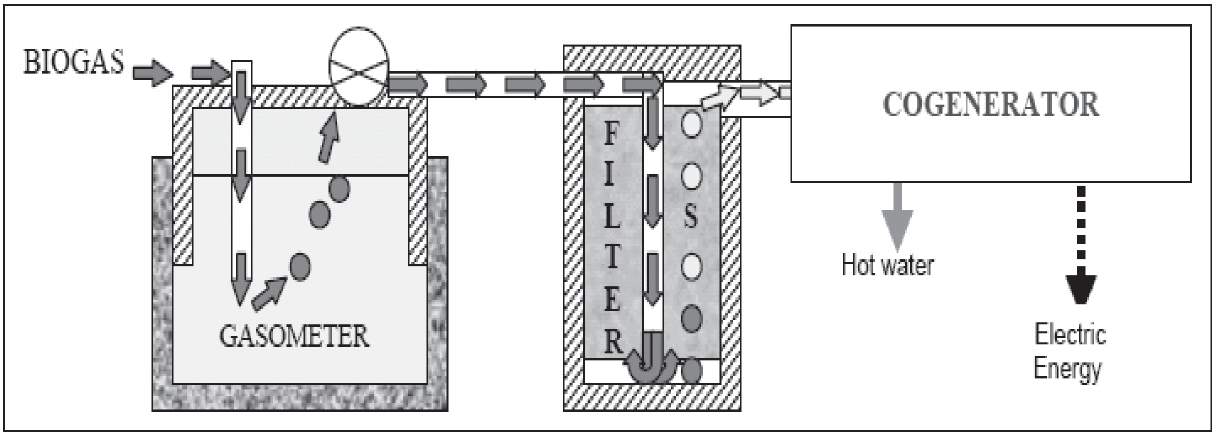


Figure 4 - The storage and biogas purification

Compact cogenerators, using internal combustion engines, can utilize from 50 to 70% of the energy available in the biogas as thermal energy and from 23 to 30 % in the form of electrical energy. Total yield of this cogeneration system varies from 80 to 90% (SILVEIRA,1994). Produced heat by these plants is available in temperature range between 80°C a 450°C. Figure 5 shows the operation of this system and a picture of this unit.

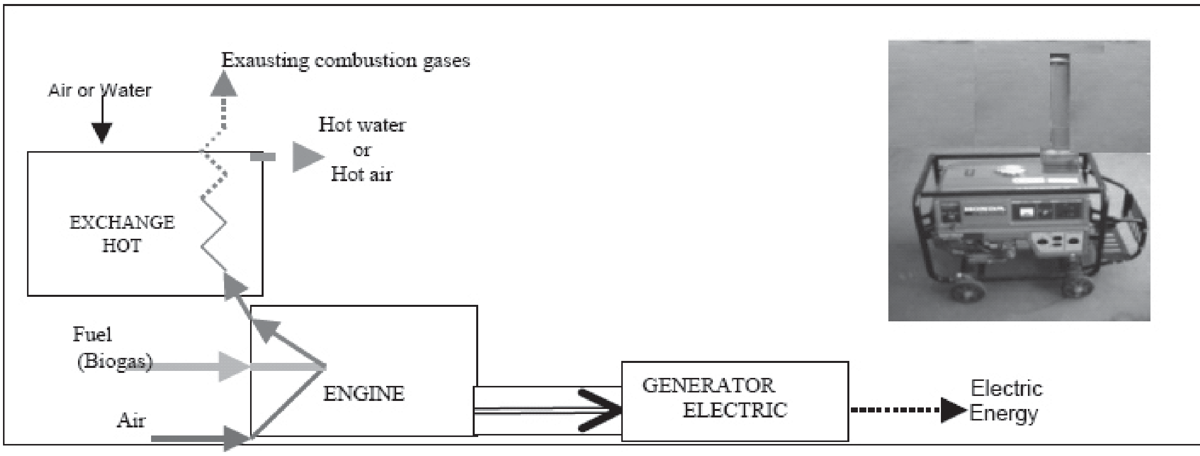


Figure 5 – Picture and sketch of operation of the system, showing heat recovery of the exausting gases

## Configuration of the system for water reuse for fertilization and irrigation

Irrigation and fertilization with biofertiliazer, the treated effluent, is being performed by means of drop piping close to the roots of trees of a wood under formation, in the UNESP Campus at Guaratinguetà, São Paulo, Brazil.

## MiniETE Associated to an Energy Cogeneration System and Water Reuse

The type of miniETE built at the Guatinguetà Campus of UNESP, is called a cllective version; with a useful volume of 70 $m^3$/day with possibility of treating sewage produced by a popuklation of 1000 people. This system is compared analyzing three cases: case 1 – traditional system by activated sludge; case 2 – anaerobic-aerobic integrated system; case 3 – anaerobic-aerobic-anoxious integrated associated to a cogeneration unit and water reuse. Figures 6, 7 and 8 show the operation of all three cases.

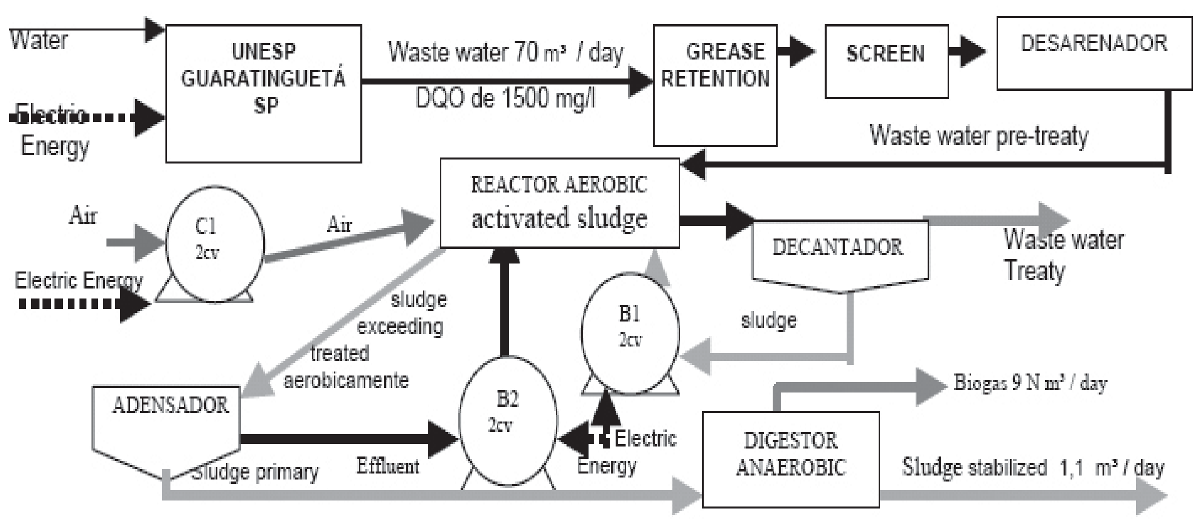


Figure 6 – Operating scheme of a traditional system with activated sludge

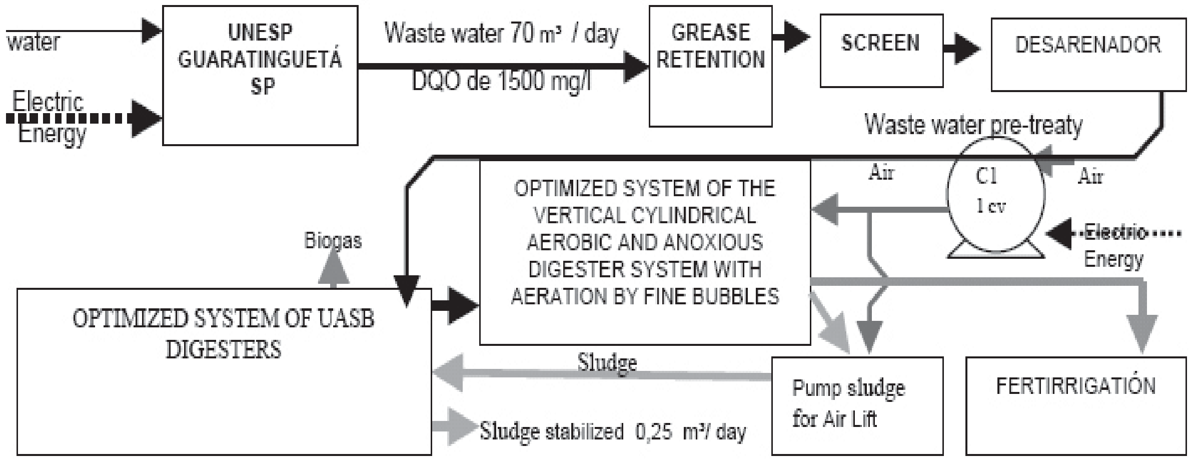


Figure 7 – Anaerobic-aerobic treatment

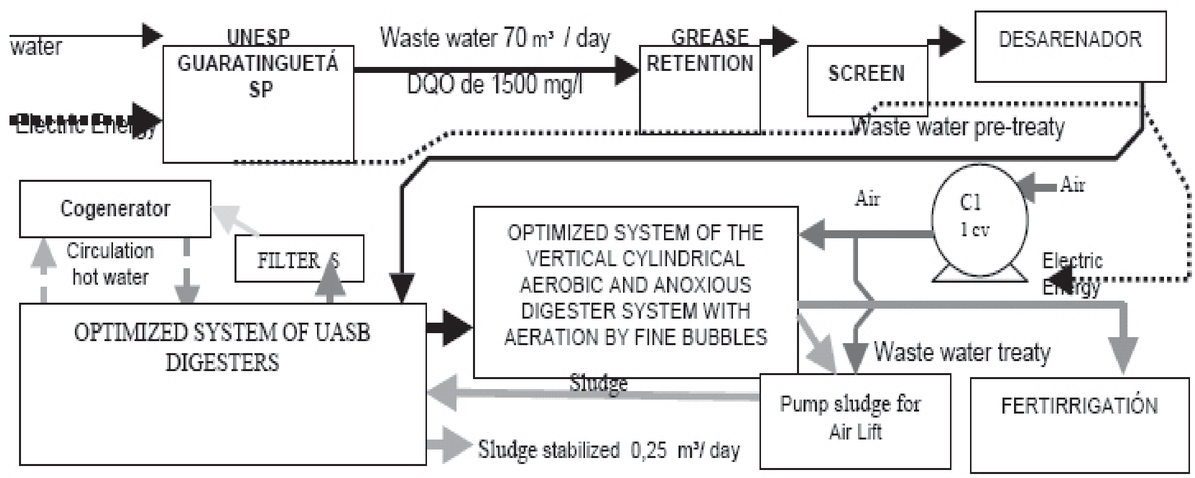


Figura 8 – Anaerobic – aerobic-anoxious treatment associated to cogeneration and water reuse

The follwing values have been adopted: Pel = 0,075 US$/kWh; Ptl = 5 US$/m³; average COD of sewage of 1500 mg/l; r = 12% /yr, H = 8760 h/yr; maintainance cost for the sludge system = 0,003% of Ipt; maintainance cost of TOTEM system = 0,003% of Ipt; Pet = 0,650 US$/m³; (Sao Paulo State Sanitation Company – SABESP tariff).

These values were adopted in basis of locations where will be installed all three configurations. Production of about 30 m³ of biogas per day is sufficient for the operation of the cogeneration system during only ten hours. Therefore, the option was to operate from 1:00 AM to 10:00 AM for the production of electric energy for the aerobic part of the system and warm water for the heating of the UASB´s. During the remaining hours of the day electrical energy will be supplied by the local power company.

Table 1 – Adopted data of miniETE´s configurations as given in figures 5, 6 and 7

| | Case 1 | Case 2 | Case 3 |
|---|---|---|---|
| Production of biogas [m³/day] | 9 | 27 | 30 |
| Qeb [m³/ day] | 70 | 70 | 70 |
| Pl [m³/ day] | 1.10 | 0.25 | 0.25 |
| Ptl [US$/m³] | 0.0310 | 0.0068 | 0.0068 |
| Power equipaments [cv] and utilization per day [hours] | C1 = 2 ; (24 hours)<br>B1 = 2 ; (6 hours)<br>B2 = 2 ; (12 hours) | C1 = 1 ; (24 hours) | C1 = 1 ; (24 hours) |
| Ereq per day of equipaments [kW]<br>Total | C1 = 35.80<br>B1 = 8.95<br>B2 = 17.90<br>62.66 | C1 = 20.00<br>20.00 | C1 = 20.00<br>20.00 |
| Ipl [US$]<br>Total | activated sludge = 60,000.00<br>60,000.00 | UASB = 30,000.00<br>Aerobic-Anoxic = 15,400.00<br>Fertirrigation = 8,400.00<br>53,800.00 | UASB = 30,000.00<br>Aerobic-Anoxic = 15,400.00<br>Fertirrigation = 8,400.00<br>TOTEM7 = 9,000.00<br>62,800.00 |
| CmETE [US$/m³]<br>Total | activated sludge = 0.333<br>0.333 | UASB = 0.003<br>Aerobic-Anoxic = 0.18<br>Fertirrigation = 0.0164<br>0.1895 | UASB = 0.003<br>Aerobic-Anoxic = 0.18<br>Fertirrigation = 0.0164<br>TOTEM7 = 0.29<br>0.4894 |

Table 2 - Specification of module the cogeneration tip TOTEM

| Manufacture | Model | Ep [kW] | Ec [kW] | Ecomb [kW] | Ta [ºC] | Mb [m³/h] |
|---|---|---|---|---|---|---|
| Biklim | TOTEM | 7 | 21 | 29 | 80 | 3,0 |

## ETE´s Technical and Economical Analysis

The development cost is defined as the plant construction cost and the cost of the electromechanically equipment. The operational cost is defined as the expendable items and the cost of all services necessary to thru final sludge and effluent disposal. The estimated cost of the plant ready to operate (Ipl), includes the cost of facilities, cogeneration system and fertilization and irrigation system, as applicable.

The results are as follows:

$$Cet = \frac{Ipt * F}{H * Qeb} + CoETE + CmETE \quad (1)$$

$$F = \frac{q_k * (q-1)}{q^k - 1} \quad (2)$$

$$q = 1 + \frac{r}{100} \quad (3)$$

$$R = H * \frac{Qeb}{24} * (Pet - Cet) \quad (4)$$

In case 1, traditional treatment (Aerobic with activated sludge), one finds:

$$CoETE = \frac{Ereq * Pel}{Qeb} + Ptl = 0.87 US\$/m^3 \quad (5)$$

In case 2, anaerobic-aerobic-anoxious treatment plus fertilization and irrigation the results are:

$$CoETE = \frac{Ereq * Pel}{Qeb} + Ptl = 0.224 US\$/m^3 \quad (6)$$

In case 3, anaerobic-aerobic-anoxious treatment plus fertilization and irrigation with cogeneration, one finds:

$$CoETE = \frac{\left(Ep * \frac{10}{24} - Ereq\right) * Pel}{Qeb} + Ptl = 0.087 US\$/m^3 \quad (7)$$

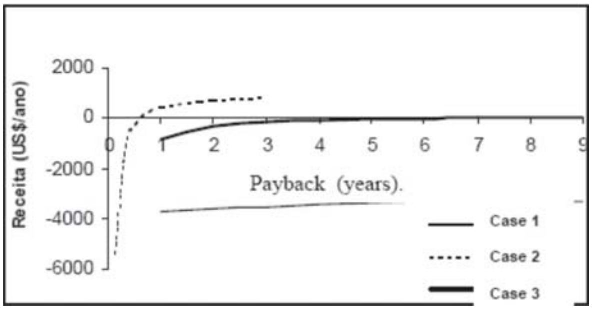


Figure 9 – Graphical comparison between cases 1, 2 and 3: Revenues (US$/yr) versus Payback (years)

## Discussion of Results

With the development of the proposed system it is certainly possible to save good quality water, decrease electric power consumption and discard an effluent with biological and chemical characteristics much less aggressive to the environment.

In Figure 9 it is noted that case 1 is practically not viable, since the revenues indicate a negative return rate. In case, the investments are paid after seven months. In case 3, the investment is paid after seven years, but one should consider the saving of electric power.

It should be noted that the investment is amortized for other values of the interest rate, but for this work an annual value of 12% has been adopted.

## Conclusions

In case 1, a first conclusion is that the system is economically not viable, although the environmental benefits are equivalent to cases 2 and 3.

Case 2, with a payback of only seven months, indicates a system with great advantages as far as economy is concerned, since the operational cost is very small besides the fact that the volume of sludge produced is 75% lower than case 1.

Case 3 imposes a grater capital investment since in Brazil the cogeneration unit has to be imported. On the other hand implies a lower operational cost, with the additional possibility of national production of all equipments.

In case of an ETE for a food or agricultural industry, operational cost tend to decrease because an increased production of biogas due to a larger amount of organic material s in the process residues. This could give a surplus of electric power to be sold to local power company.

The development of the system is very interesting from a point of view both ecological and energetically since it represents a viable alternative by concluding environmental protection and energy production.

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