DESIGN OF OPTIMAL BIOGAS BUFFER INVENTORY IN WASTE TREATMENT FACILITIES

F. A. Batzias, N. P. Nikolaou and A. S. Kakos

Department of Industrial Management, University of Piraeus, GREECE
phone: (+301) 4142321, e-mail: fbatzi@unipi.gr

Abstract

This work deals with the optimal design of a biogas buffer inventory in an organic treatment facility. This inventory is made by saving/storing part of the biogas produced via anaerobic digestion. Saving is achieved by using solar energy, which we cannot store in an economic way. The stochastic optimization disciplines used are: (i) minimization of solar collector area in order to minimize the fixed cost and (ii) standardization of confidence as regards the avoidance of biogas shortage during a calendar year period. For the solution of the problem we designed and developed a proprietary software package performing Monte Carlo filtering through simulated sampling to determine a near-optimal solution on time-dependent basis. The results obtained showed that the computational approach adopted is quite satisfactory as regards (i) efficiency in finding the design/operation parameter-values and (ii) flexibility by providing the means to easily extend or transform the procedure to cover external biogas demand under uncertainty.

Keywords

Biogas production, buffer inventory, waste treatment, optimization, solar energy, Monte Carlo simulation

Introduction

In many islands of the Aegean Sea there is a shortage of water and energy, especially during the summer when the population increases dramatically due to tourism. For the same reason the demand for sanitary services and wastewater treatment capacity is highly increased. Fortunately, during these summer months there is also an increased availability of solar energy. The aim of this paper is to present a system of optimal saving energy produced in a wastewater treatment plant where biogas is produced through anaerobic digestion. The raw material used is either municipal sewage sludge coming from primary sedimentation and secondary thickening in a biological treatment facility or agricultural/industrial biodegradable wastes. Optimization of energy saving is achieved by using solar energy to substitute biogas usually burned to keep the fermenter or anaerobic digester within the range of 35-38^{o} C by the aid of a heat exchanger. The key element in this combination is the creation of a biogas buffer inventory that will make the facility energy independent and possibly an energy supplier to other industrial/agricultural biogas consumers in the vicinity. This buffer inventory requires a careful design, as input variables in the biogas production system are stochastic due to uncertainty as regards the characteristics of the processed organic waste.

Simulation of the process

By simulating the anaerobic digester to a Continuous Flow Stirred Tank Reactor (CFSTR), as it is shown in Figure 1, we obtain the following balance equations, according to the general expression *Accumulation = Input - Output + Production – Consumption.*

For substrate: $V\, {dS}/{dt} = Q\,S_o - Q\,S - r_s\,V$, for biomass: $V\, {dX}/{dt} = Q\,X_o - Q\,X + r_x\,V$

where S_o, S inflow/outflow substrate concentration, expressed in BOD respectively

X_o, X inflow/outflow biomass concentration respectively

r_s, r_x rates of substrate consumption and biomass production respectively according to the widely used Monod kinetic models:

$$r_s = k\,S\,X / (K_s + S),\quad r_x = Y\,k\,S\,X / (K_s + S) - k_d\,X$$

K_s	substrate saturation const.	V	volume of digester
Y	biomass synthesis const.	Q	volumetric flow
k	max specific substrate consumption rate const.	k_d	endogenous rate const.

By substituting the rate expressions, the material balances become

$$V\,dS/dt = Q\,S_o - Q\,S - k\,S\,X\,V / (K_s + S) \qquad (1)$$
$$V\,dX/dt = Q\,X_o - Q\,X + Y\,k\,S\,X\,V / (K_s + S) - k_d\,X\,V \qquad (2)$$

In practice, the biomass concentration in the feed stream is negligible, i.e.: $X_o \approx 0$.
Therefore, we obtain the following relations for steady state conditions:

$$0 = Q\,S_o - Q\,S - k\,S\,X\,V / (K_s + S) \qquad (3)$$
$$0 = - Q\,X + Y\,k\,S\,X\,V / (K_s + S) - k_d\,X\,V \qquad (4)$$

By defining the residence time $\Theta = V / Q$, the last equation gives the substrate concentration S, which is an important dependent variable of the simulated system:

$$S = K_s\,(1 + k_d\,\Theta) / [(\Theta\,(Y\,k - k_d) - 1] \qquad (5)$$

For the estimation of the biogas, produced, it is widely accepted that the quantity of methane released can be calculated by means of the equivalent mass in oxygen, obtained by the simple equation of perfect combustion $CH_4 + 2\,O_2 \rightarrow CO_2 + 2\,H_2O$ i.e. 16g or 1 mol methane is equal to 64g BOD or 1 / 64 mole methane is equal to 1 g BOD (on dry basis, not considered as concentration).

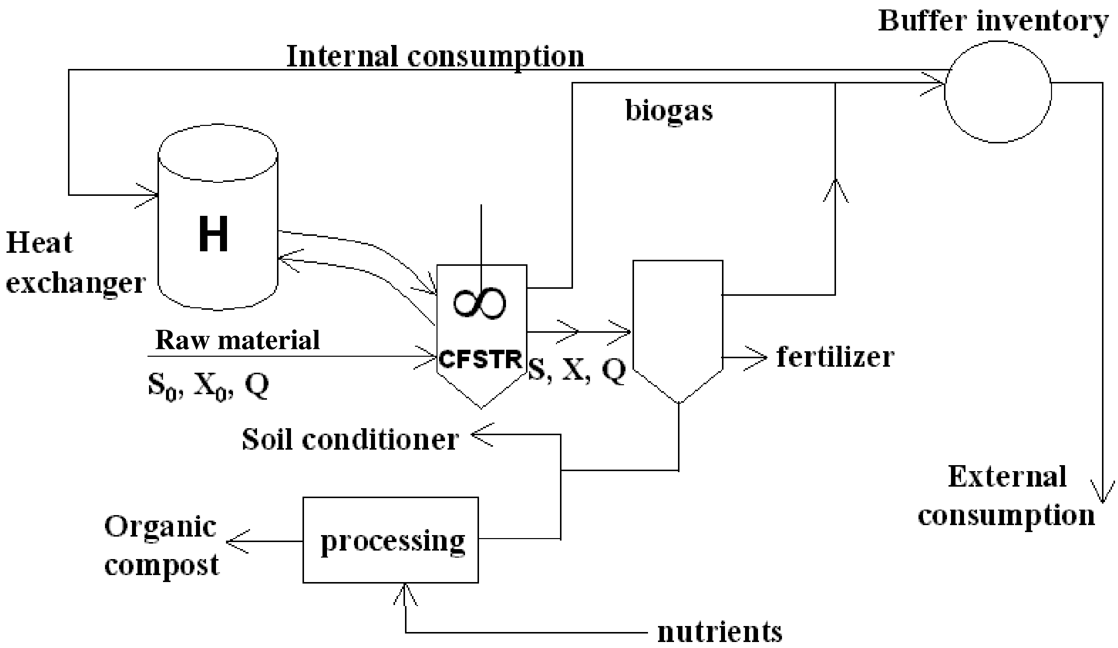


Figure 1 Anaerobic digester, simulated to CFSTR, in series with the second stage tank. The buffer inventory provides biogas to the heat exchanger H.

As the volume of 1 / 64 mole methane is 22.4 / 64 = 0.35 L, under normal conditions (0 ^{o}C and 1 Atm), we conclude that the methane production under normal conditions is 0.35 L / g BOD. On the other hand, a typical formula for biomass is $C_5H_7NO_2$ with molecular weight 113. From the simple equation of oxidation, $C_5H_7NO_2 + 5\ O_2 \rightarrow 5\ CO_2 + 2H_2O + NH_3$, we conclude that the required oxygen is 5 * 32 / 113 = 1.42 g / g oxidized biomass.

Taking into account that the biomass produced Q ΔX (which is removed by means of outflow so that the steady state equilibrium does not change) consumes constituents coming from the decomposition of substrate, resulting to a decrease in biomass available for biogas production, we can calculate the production of methane $G \in [L^3T^{-1}]$ by means of the relation

$$G = G_0[(S_0 - S)\,Q - 1.42\,Q\,\Delta X],\ \text{where}\ G_0 = (273 + T\ {}^{o}C)\ 22.4 / (273 \cdot 64),\ \ G_0 \in [M^{-1}L^3]$$

Maximization of Efficiency

To maximize the efficiency $E = (S_0 - S) / S_0$ or $E = 1 - S / S_0$ of a system containing *n* digesters in parallel, in the general case, we have to minimize the outflow substrate concentration S, which is the mean of the S_i-values weighted by the corresponding (Q_i/Q)-values. This arrangement is shown in Figure 2, where the feed Q is divided into Q_1, Q_2, …, Q_n by a controller operating with *n-1* degrees of freedom (df). Each digester is heated by an exchanger H_i, and the effluent enters a second-stage tank arranged within a set of *m* such tanks ($m<=n$). The buffer inventory consists of q storing tanks, which provide biogas to the heat exchangers (internal consumption) and possibly to an external consumer (e.g. a sea water desalination plant which might operate in the vicinity to provide potable water, a scarce resource for most island in the Aegean Sea). The obvious relation among the stream flows $Q_1, Q_2, \ldots Q_n$ leaving the first-stage digesters is $S_1 Q_1 + S_2 Q_2 + \ldots + S_n Q_n = S Q$ as $Q = Q_1 + Q_2 + \ldots + Q_n$, which by means of eq. (5) is written as follows:

$$S = S(Q_1, Q_2, \ldots, Q_n) = \frac{1}{Q}\{\sum_{j=1}^{n} \frac{K_s(Q_j - k_d V_j)}{(Y * k - k_d) - Q_j} Q_j\}$$

To minimize the S-function, we define the quantity F so that:

$$F = F(Q_1, Q_2, \ldots, Q_n ; \lambda) = S(Q_1, Q_2, \ldots, Q_n) + \lambda * \{(\sum_{j=1}^{n} Q_j) - Q\}, \lambda \in \Re$$

where λ is the Lagrange multiplier and f (Q_1, Q_2, .., Q_n) = $Q - \sum_{j=1}^{n} Q_j$ is the constraint under which the minimum S should be identified.

To find such constrained minimima we require that $\frac{\partial F}{\partial Q_i} = 0, i = 1,\ldots,n$ and that the associated Lagrange determinants Δ_i, i=1, 2,..., n should all have a negative value.

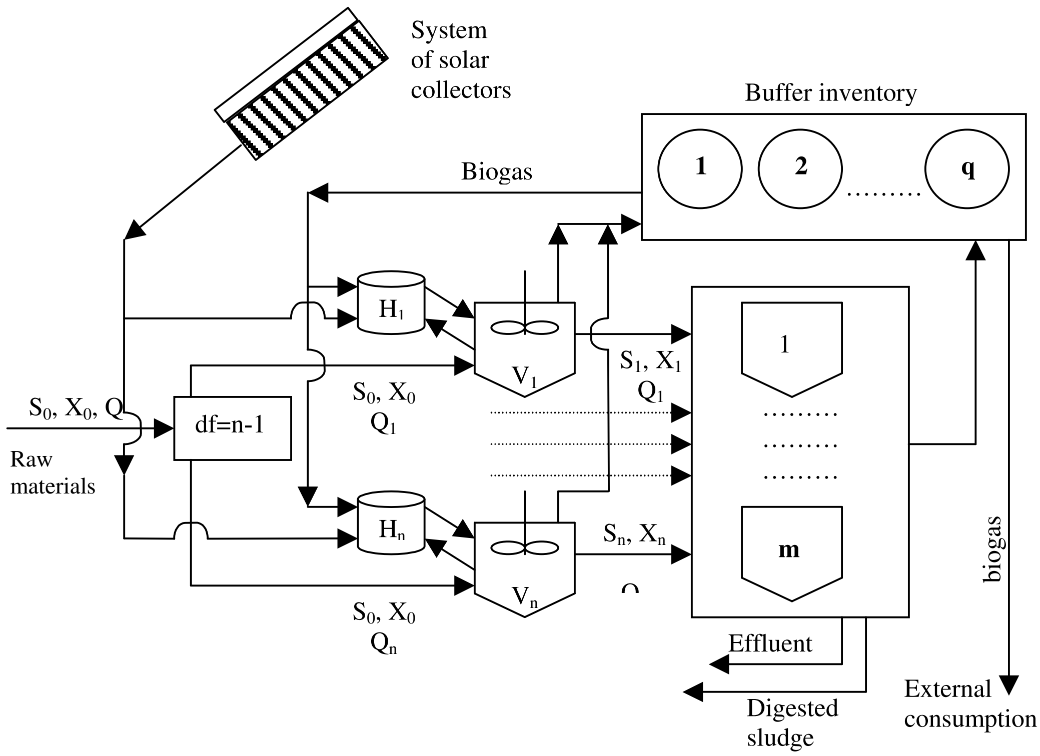


Figure 2 A complete system containing n digesters in parallel and a buffer inventory with q tanks supplying biogas to both; the internal consumption of n heat exchangers and the external demand.

However, one of the solutions for

$$\frac{\partial F}{\partial Q_i} = \frac{-1}{Q}\left\{\frac{2K_s(\frac{Q_i}{V_i})(Y*k-k_d) - K_s\left(\frac{Q_i}{V_i}\right)^2 + k_d K_s (Y*k-k_d)}{(Y*k-k_d)-\frac{Q_i}{V_i}}\right\} = 0$$

is $\frac{Q_1}{V_1} = \frac{Q_2}{V_2} = \ldots = \frac{Q_n}{V_n} = \frac{Q}{V}$ which apparently makes the aforementioned determinants negative.

It should also be noted that $\frac{\partial^2 F}{\partial Q_i \partial Q_j} = 0, \forall i \neq j$ and that

$$\frac{\partial^2 F}{\partial Q_i^2} = \frac{-1}{Q}\left\{\frac{42K_s V_i^2 (k_d - Y*k)*Y*k}{(Q_i + V_i(k_d - Y*k))^3}\right\}$$

Solar Energy Assisted Thermal Balance

To estimate the optimal biogas buffer inventory, we have to make a thermal balance over each digester. Let N_i be the thermal requirements for the digester i, which is the sum of thermal losses and sludge heating from ambient temperature (e.g. 18°C) to 35°C.

$$N_i = m\,c\,(T_o - T_a) + U\,A\,(T_o - T_s)$$

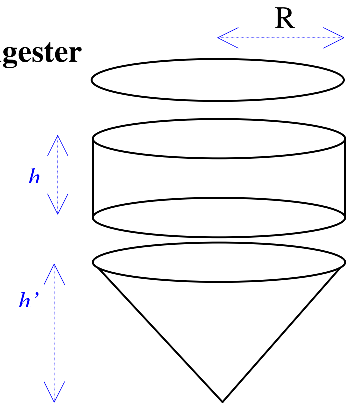
where

m	mass sludge inflow	T_s	soil temperature
c	specific heat coefficient	T_a	ambient temperature
U	overall coefficient of heat transfer	T_o	optimal temperature of digestion
A	cross-sectional area through which the heat loss occurs		

To minimize thermal energy loss for a digester of the following geometry, with predetermined volume V, we must optimize its dimensions, under the empirical constraints:

$6 < 2R < 35$ m , $7.5 < h+h' < 14$ m and $h' \approx R/4$

Parts of the digester



Surface area of each part

$$E_{cover} = \pi R^2$$

$$E_{cylinder} = 2\pi R h$$

$$E_{cone} = \frac{\pi R^2 \sqrt{17}}{4}$$

$$V_{total} = \pi R^2 (h + \frac{R}{12})$$

Case I. There is no change in U-value over all surface area of the digester.

$$R_{optimal} = \sqrt[3]{\frac{12V}{\pi(10+3\sqrt{17})}}\ ,\ h_{optimal} = \frac{V - \pi R^3/12}{\pi R^2}$$

Case II. There are three U-values: U_w for the wall cylindrical surface, U_c for the cover, U_b for the bottom conical surface. The results are:

$$R_{optimal} = \sqrt[3]{\frac{12V\ U_w}{\pi(12U_c - 2U_w + 3U_b\sqrt{17})}}\ ,\ h_{optimal} = \frac{V - \pi R^3/12}{\pi R^2}$$

The usual tabulated empirical values of U_w, U_c and U_b confirm that the denominator $(12U_c - 2U_w + 3U_b\sqrt{17})$ is always positive.

E.g., for a unique digester with input values S_0=6500 mg/L and Q=100 m^3/d, we can use the typical values Y=0.04, k=6.67d^{-1}, K=2,224 mg/L for 35 ^oC to obtain the residence time of 5.03 d, which gives a volume ≈ 1,500 m^3 if a safety factor SF=3 is adopted [Batzias & Koronakis, 1984]. By applying the formulae of case II for this predetermined volume and U_w=0.72, U_b=0.82 and U_c=0.95 ($W/m^2{\cdot}{}^oC$), we obtain R=5.898.

For a digester surrounded by earth embankments that serve as insulation, with T_s=12 ^oC, T_a=18 ^oC and T_0=35 ^oC, the energy balance can be stated as follows:

	A (m^2)	U ($W/m^2{\cdot}{}^oC$)	Heat Losses (J/d)
Walls	331.9547	0.72	4.5E+08
Bottom	194.8583	0.82	3,18E+08
Cover	189.0403	0.95	3.7E+08
TOTAL			***1.149356E+09***

Energy Balance (GJ/d)	
Energy Produced	6.795
Energy Losses	1.149
Sludge heating	7.380
Deficit (GJ/d)	***1.73***

Optimization of Biogas Buffer Inventory

The problem we try to solve herein is the determination of optimal level of a biogas buffer inventory, formed by using solar energy in heat transfer instead of biogas. The objectives to be achieved are (i) minimization of solar collector area in order to minimize the fixed cost and (ii) standardization of confidence (e.g. at 95%) as regards the avoidance of biogas shortage during a calendar year period.

To solve the problem in its general form, an original Windows-based software application was developed including several algorithmic procedures to cope with various combinations of parameter values that might occur in practice.

An "exhaustive search" approach has been applied in this particular type of problem. Within a user-defined range, all possible values for the surface area of the solar collector are examined. The searching step is also a parameter that is apparently defined by the end-user (see Figure 3).

For every value of the solar collector area examined, a collection of random numbers is drawn. These numbers simulate the randomness of the *volumetric flow rate* (Q) which is assumed to be a random variable following the normal distribution ($Q \sim N(\mu_Q, \sigma_Q)$). The size of the collection as well as the mean value μ_Q and the standard deviation σ_Q of Q are user-defined parameters.

In the same way, values of influent Biochemical Oxygen Demand (BOD) are simulated through a similar random number generation process under the assumption that BOD is a normally distributed random variable (i.e. $BOD \sim N(\mu_{BOD}, \sigma_{BOD})$). Once again the user is free to define a mean value μ_{BOD} and a standard deviation σ_{BOD} of his choice. In this way a Monte Carlo simulation procedure for the *Buffer Inventory System* is set up.

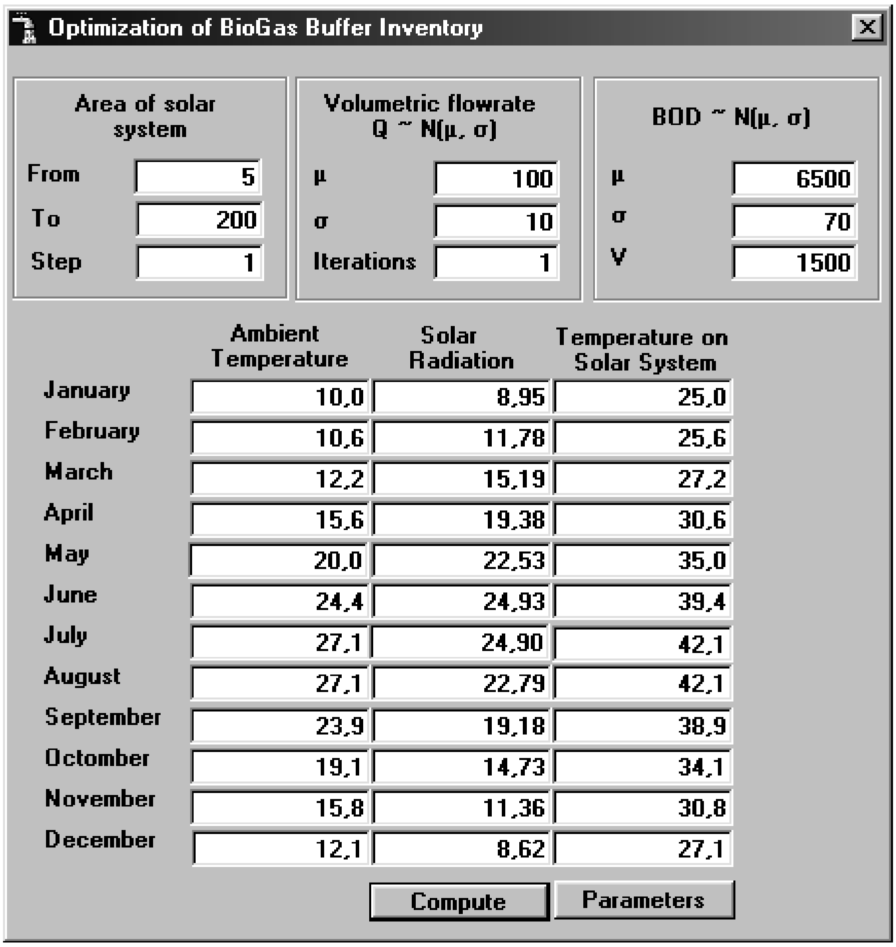


Figure 3 Input data window for Monte Carlo simulation

The rest input data used for the simulation have been extracted from the work of Batzias & Koronakis (1984). These include tables with typical monthly values for the ambient temperature, solar radiation and the temperature on the solar collector.

The application may also be used in order to examine a single value for the area of the solar collector. In such a case, the search range is diminished in a sole point. Likewise, the aforementioned procedure is transformed from stochastic to deterministic by using zero standard deviations, resulting to automatic exclusion of the Monte Carlo subroutines.

When external biogas consumption is also taken into account, as in the case of desalination plant operating in the vicinity (see Batzias & Sigalas, 1989) the biogas demand per typical day of each month should be entered within the input vector as a stochastic variable.

After the determination of the input parameters, the following quantities are calculated:

- The amount of the biogas energy produced per typical day of each month
- Thermal losses per typical day of each month
- Energy required for the initial sludge heating of the biomass per typical day of each month
- The amount of the energy saved by the solar collector per typical day of each month

For each combination of values (Area, Q, BOD) the system functionality is simulated for a period of one calendar year (12 months). This is sufficient since a whole period of solar radiation activity is covered.

Since the solar energy produced cannot be efficiently stored, it should be consumed right away. The surplus of the biomass energy produced is stocked (in the form of biogas) so as to be used during the low solar radiation winter months. Once this goal is achieved, the system will be, from an energy point of view, self-sufficient throughout the year.

The criteria of identifying the optimal area of the solar collector are two:

1. the collector's area should be of such size so as the solar energy produced is adequate for the system needs. However, the energy produced by the solar collector should be no more than the total energy consumed by the system during the hottest month of the year. In this way no solar energy is wasted. Therefore, this criterion favors the area of the solar collector which yields a zero or near zero energy balance in a one year period.
2. the probability of having a yearly deficit in the biogas should be no more than a predetermined percentage (e.g. 5%).

In each stage, the results are automatically exported to MS Excel so as to facilitate the investigation of further conclusions. The application was developed in MS Visual Basic (VB 6.0).

After running the simulation program for several times, we found that reliable convergence to optimal solutions was always achieved in reasonable time. Reliability was checked by measuring relative deviations among the solutions found with different initial values of independent variables and parameters. Some representative results are given in Figures 4-9.

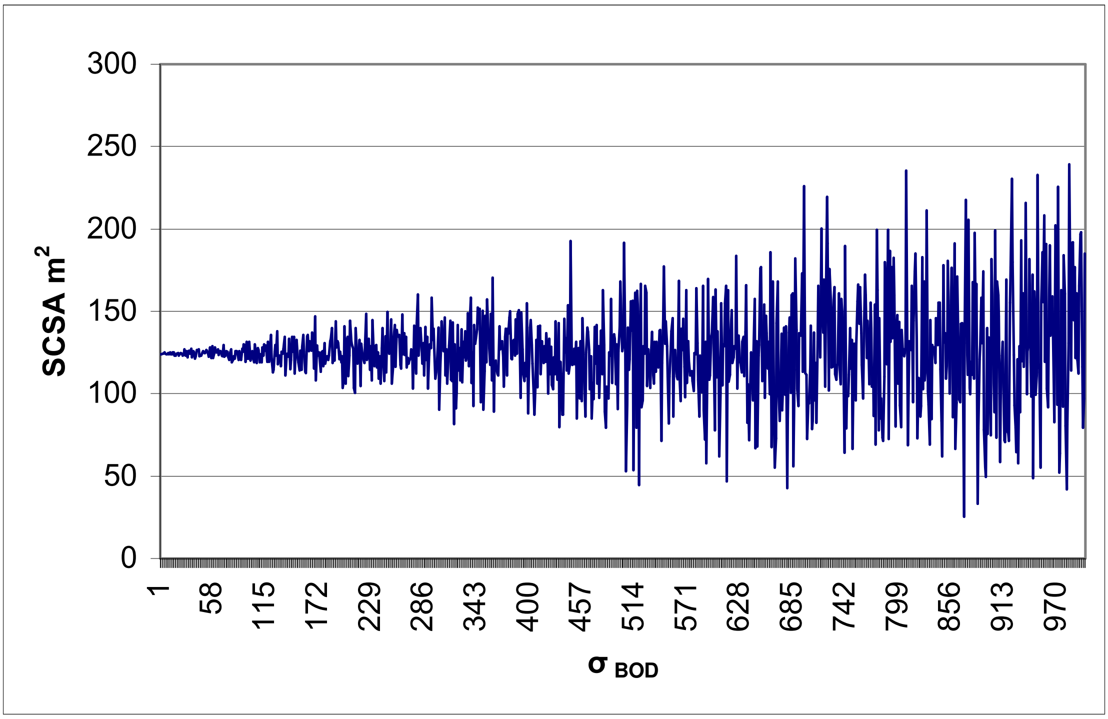


Figure 4 Dependence of Solar Collector Surface Area (SCSA) on standard deviation of influent BOD with mean value 6,500 mg/l.

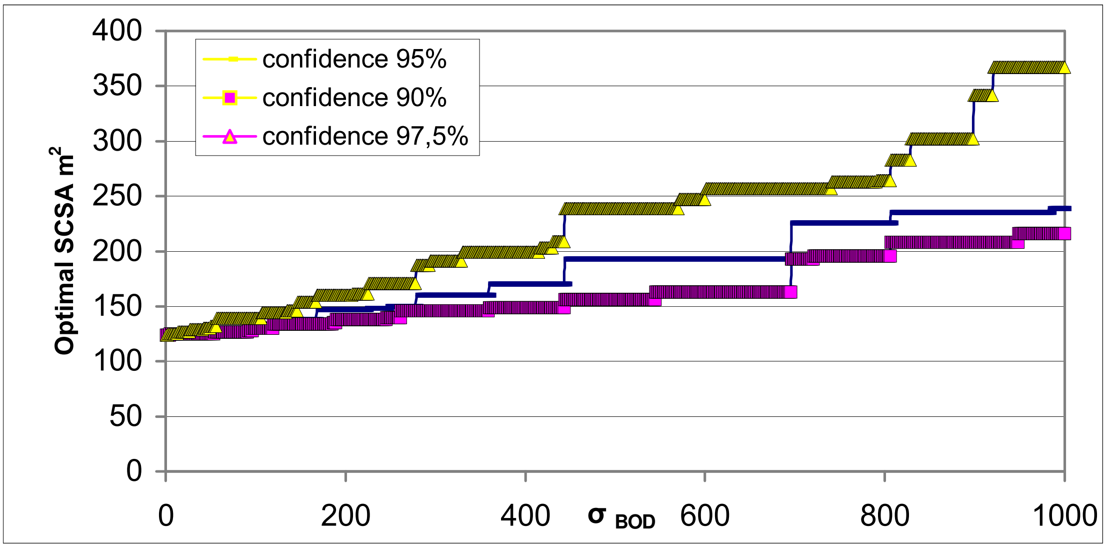


Figure 5 Dependence of Optimal SCSA on standard deviation of influent BOD for three confidence levels adopted as criteria of optimization (Monte Carlo simulation filtering).

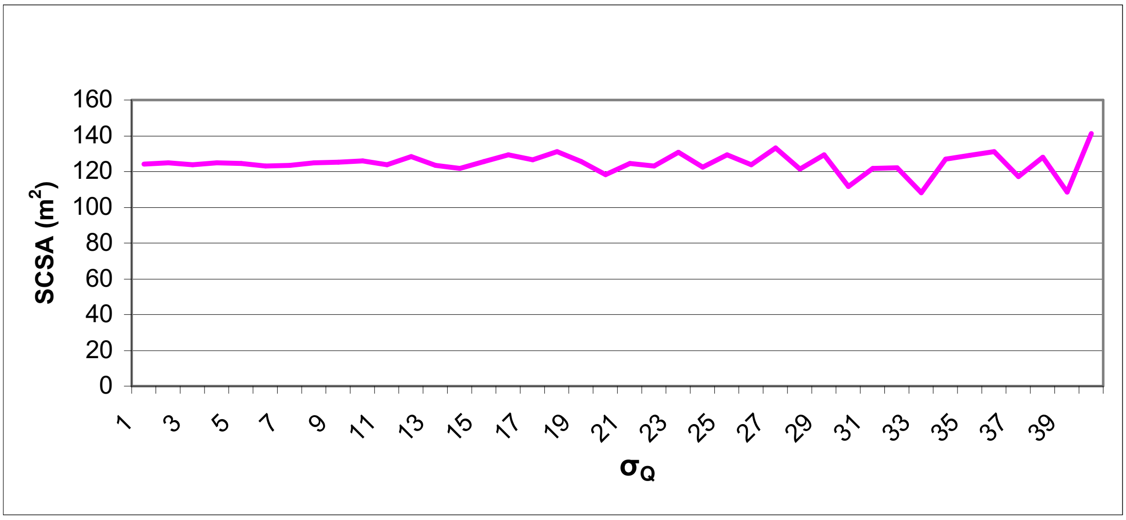


Figure 6 Dependence of Solar Collector Surface Area (SCSA) on standard deviation of volumetric flowrate with mean value Q=100m^3/d.

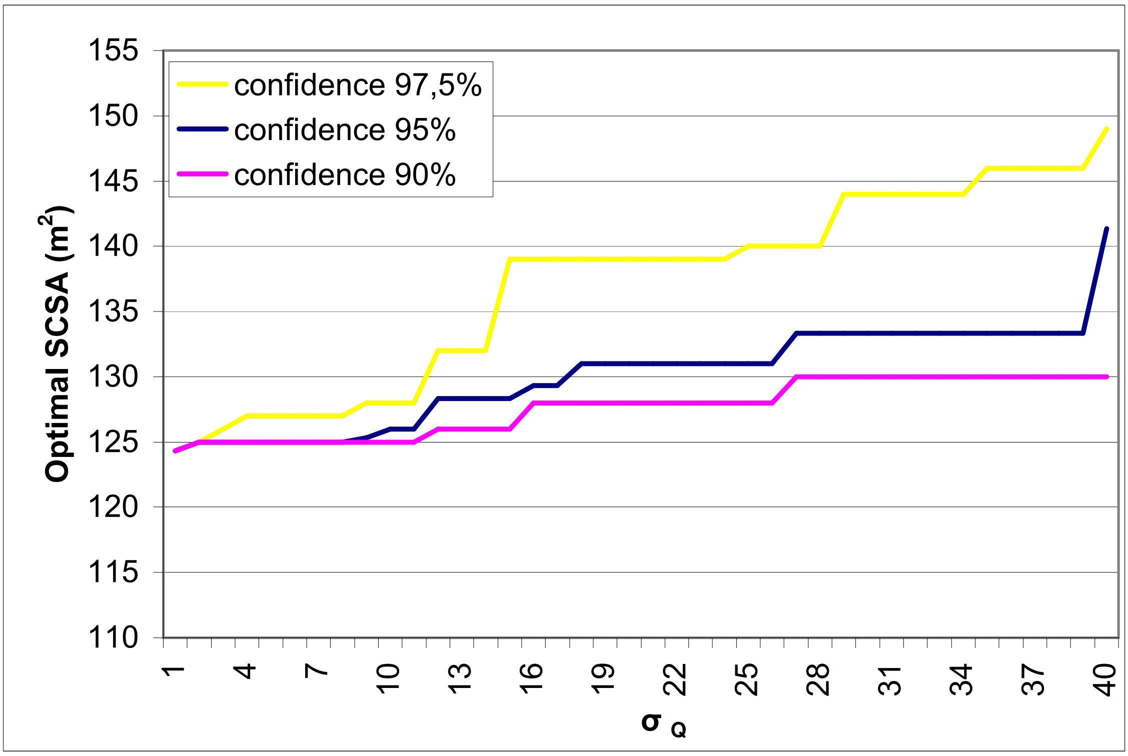


Figure 7. Dependence of Optimal SCSA on standard deviation of volumetric flow rate Q for three confidence levels adopted as criteria of optimization (Monte Carlo simulation filtering).

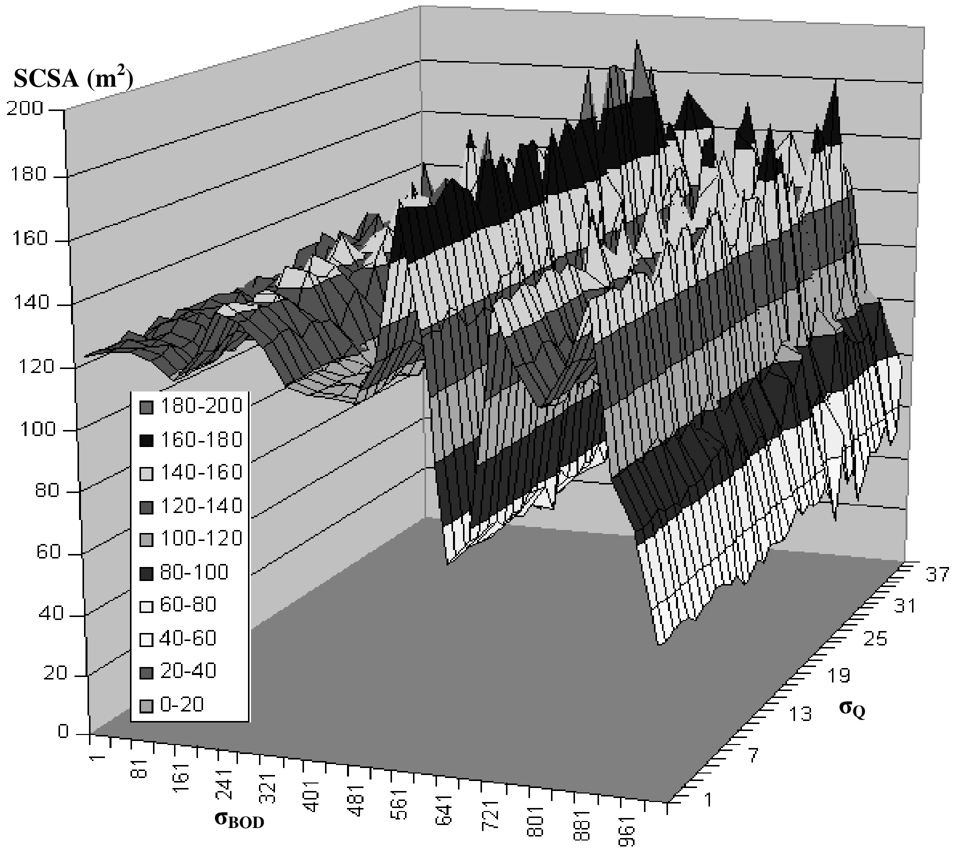


Figure 8 Combined dependence of Solar Collector Surface Area (SCSA) on standard deviations of influent BOD and volumetric flowrate Q.

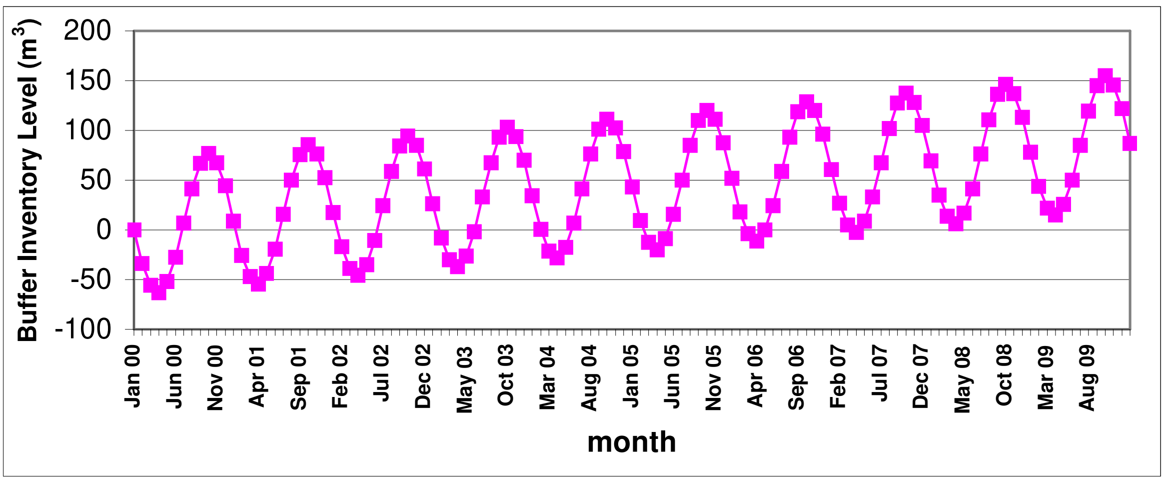


Figure 9 Evolution of biogas buffer inventory 65% methane in a ten-year period, including the startup period (SCSQ = 124 m^2).

Discussion

Although anaerobic digesters deployment within the EU, now with a total generating capacity of 300 MW, is expected to reach 1,000-2,000 MW by 2010, most digesters work under aerobic conditions because they exhibit the following advantages:

1. A biological stable end product is produced
2. The stable end product has no odor; therefore, land disposal is feasible.
3. Because construction is simple, capital costs for aerobic digesters are lower than for anaerobic digesters.
4. Aerobically digested sludge generally has good dewatering properties
5. For biological sludges, about the same percent TVS (Total Volatile Solids) reduction can be achieved in aerobic digestion as can be achieved in anaerobic digestion.
6. Supernatant liquors from aerobic digestion have a lower soluble BOD content (regularly less than 100 mg/l) than those for anaerobic digestion. This is a significant characteristic for keeping the operation within a percent vector of parameter – values, because many treatment facilities have been overloaded due to recycling of the high-BOD supernatants liquor from anaerobic digesters.
7. Aerobically digested sludges have a higher fertilizer value than do those from anaerobic digestion.
8. There are few operational problems with aerobic digestion than with the more complex anaerobic form because the system is more stable. Therefore, lower maintenance costs and less skilled labor, used in plant operation, will be required.

The present paper offers further support to the diffusion of anaerobic digesters, especially in the Mediterranean countries where solar collectors are widely used to provide warm water. Moreover, the availability of inexpensive solar energy, especially during the summer period when demand for sanitary services is at maximum, assures that temperature in the anaerobic digesters will be kept at the desired level while the biogas buffer inventory assures the same possibility all year round. Therefore we add a significant operational advantage on behalf of anaerobic digestion or against its rival, the aerobic digestion, which also exhibits the following disadvantages:

1. Higher power cost, associated with supplying the required oxygen, results in high operating cost, which becomes significant in large facilities. On the contrary, anaerobic digestion produces a significant amount of biogas (0.5 – 0.75 m^3/kg TVS loaded or 0.75-1.12 m^3/kg TVS destroyed or 28 m^3/kg / 1000 cap-day, with 65 methane and a low heating value of 17-25 MJ/m^3). A comparison between the two types of sludge stabilization shows that aerobic digestion is energy-intensive, whereas a considerable net energy gain can be accomplished with anaerobic digestion, especially in the case that the suggested herein schema of using solar energy to form a biogas buffer inventory is adopted.
2. Solids reduction efficiency varies with temperature fluctuation.
3. Gravity thickening following aerobic digestion generally results in a supernatant high in solids concentrations.

4. Some sludges apparently do not dewater easily by vacuum filtration after aerobic digestion.

It is worthwhile noting that the term ‘solid organic waste’, which characterizes the raw material used, has recently obtained a broader meaning by including all organic-biodegradable-waste with moisture content below 85-90%. In fact, there are many agricultural and industrial wastes meeting this broad definition, but the most relevant is the organic fraction of municipal solid waste, with a daily production in EU of about 400,000 tons (Mata-Alvarez, 2000). In the special case of sludges obtained from municipal sewage treatment, about 40,000 anaerobic digesters are in operation in EU, processing around 45% of this material (Tilche & Malaspina, 1998, and estimates based on EUROSTAT, 2001).

In addition emphasis has been put recently on the investigation of co-digestion of different specific raw materials, in order to find out optimal mixtures exhibiting maximal efficiencies in both, the organic constituents stabilization and the energy production (Magbanua et al., 2001 and Dinsdale et al., 2000). On the other hand, specific raw materials resulting as byproducts in processing of agricultural products are utilized to limit severe damage that might cause upon release to the environment. In these cases, the raw material is allowed to have large moisture content and a small BOD-value. Such an example is the anaerobic processing at olive pomace, a solid residue remaining after solvent extraction from the cold-pressed olives (Tekin & Dalgic, 2000).

Last, batch anaerobic digestion of urban garbage carried out under room temperature conditions (26±4^{o}C) for long periods (e.g. 240 days) may produce cheaper biogas in countries with a hot climate (Rao et al., 2000). The adoption of the method examined in the present paper by these countries might offer additional energy saving as regularly their climatic conditions favor the usage of solar systems.

Conclusions

The application of stochastic procedures determines satisfactorily the optimal biogas buffer inventory in an organic waste treatment facility, where solar energy is used to cover part of thermal requirements of the anaerobic digesters. The optimization disciplines used, i.e. (i) minimization of solar collector area in order to minimize the fixed cost and (ii) standardization of confidence as regards the avoidance of biogas shortage during a calendar year period, can be extended to include profit maximization conditions, in case of existence of an external biogas consumer in the vicinity. The Monte Carlo filtering through simulated sampling we designed and developed in a proprietary software package gives a flexible procedure that allows for stricter or looser control of buffer inventory according to the desire of the end user. It is also proved that the stochastic procedure used simulates successfully even the startup period where unsteady-state conditions prevail as the biogas buffer inventory has not yet reached the region where stable oscillations (possibly with a smooth trend) form a quazi-equilibrium zone.

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