Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2014.951962

56 (2015) 1223–1230
October

Exergetic and economic analysis of a cheese whey wastewater anaerobic treatment plant with a cogeneration system

Aspasia A. Chatzipaschali, Anastassios G. Stamatis*

Department of Mechanical Engineering, University of Thessaly, 38334 Volos, Greece, Tel. +30 24210 74077; Fax: +30 24210 74085; email: tastamat@uth.gr (A.G. Stamatis)

Received 19 September 2013; Accepted 23 July 2014

ABSTRACT

This paper investigates the extension of an existing steam production plant in order to cover both thermal and electrical needs of a factory. The plant uses biogas produced from cheese whey (CW) wastewater anaerobic digestion treatment. For this purpose a microturbine is chosen among the commercially available microturbines. The selection of the suitable microturbine for matching with the existing system is not a trivial task: the limitations (the amount of the biogas produced), the requirements (the amount of the steam produced) of the existing system, and the specifications of the microturbine by the manufacturer must be satisfied. The system considered was studied through the development of an appropriate simulation model validated with available data. Then an exergetic and economic analysis for the extended system was carried out. The results showed that the matching performance of the microturbine with the existing system has positive effects on the exergy efficiency of the plant as well as to the incomes and savings for the factory which are significantly increased compared to the existing ones. Thus, this study proves that the anaerobic treatment of CW is a sustainable way for the factory to treat the whey it produces.

Keywords: Cheese whey; Exergy efficiency; CHP; Anaerobic digestion; Microturbine

1. Introduction

In the developed and developing countries, industrial wastewaters are becoming increasingly useful in biogas production. Among others the liquid effluents such as whey coming from dairies, which is produced during cheese and cream cheese making process, represents one of the most industrial pollutants which carry a high organic load in terms of chemical oxygen demands (COD) [1,2].

Because of this high organic load of whey, anaerobic digestion (AD) constitutes an appropriate treatment method [3] not only to remove a great amount of COD but also to produce biogas (CH_4 and CO_2) which can then be used to cover energy needs of the industry. The COD represents the maximum chemical energy present in the effluent. Since obligate anaerobic microbial communities, which are characterized by a low growth rate, convert chemical energy to methane, this is also the maximum energy that can be recovered as biogas (though losses for the energy demand of the microbes themselves have to be subtracted, as well as for material that is not degradable by anaerobic microorganisms) [4]. The COD effluent also affect the rate of methane (CH_4) produced per kg of COD removed which seems to vary [5,6]. For cheese whey (CW) it is

*Corresponding author.

estimated that one liter of this effluent can produce 45 L of biogas containing 55% methane and the expected COD removal is 80%. Thus, for each liter of CW 20 L of methane (CH_4) can be produced, which are equivalent to 700 Btu of energy production [7] (for more details see [8]).

An exergetic and economic analysis for an anaerobic treatment system installed in one of the biggest dairy industries in Greece has been carried out in a previous paper [9]. The system analyzed extends from the storage of whey accompanied by the production, up to the disposal of the treated effluent from the anaerobic reactor to produce steam for the plant thermal needs. The results indicated that this system is a sustainable investment although the exergetic efficiency of the system is rather low. This paper considers an extension of this system in order to cover both the electrical and the thermal needs of the plant. For this purpose, a real-commercial combined heat and power (CHP) gas microturbine (MGT) system has been chosen in order to fully utilize the biogas produced covering both the actual steam requirements and the constraints of the existing plant while producing electricity. MGTs are small, compact, lightweight, and simple cycle gas turbines used for energy generation applications with outputs ranging from around 25 to 300 kW [10].

Therefore, the present work examines the cooperation of a real steam production plant based on AD treatment with a commercial MGT in order to evaluate their matching performance. A model of the proposed system has been developed in Engineering Equation Solver (EES) [11] in order to carry out an exergetic analysis for the extended plant. An economic analysis concerning the extended system was also conducted using the net present value (NPV) method. Moreover, the model developed can be further used to optimize the heat and energy production needs of the plant, through certain parameters control.

2. System and model description

In the system the CW after the ultra filtration membranes is collected at ambient conditions in three stainless steel tanks each of 125 m^3. It has been considered that the main components of the CW are water (95%) and lactose (5%) and the measurement COD is approximately 60.000 mg/L. The CW from the tanks is pumped with the use of centrifugal pump to the reactor with constant flow of 6.25 m^3/h. The untreated whey is heated in the first exchanger from where the treated whey exits the reactor. The untreated whey is mixed with the recirculated whey and then the mixed flow is pumped to the reactor. The reactor is of type UASB and its shape is cylindrical. The volume of the reactor is 625 m^3 and the hydraulic retention time is about of 8 d. The entrance of the untreated whey is from the bottom of the reactor, while the outlet of biogas and the treated flow is at the top. The bacteria in the reactor are mesophilic, which means that the temperature inside the reactor is kept at 35˚C. So, before the mixed flow entering to the reactor it passes from a second heat exchanger in order to be heated at the required temperature (35˚C). The heating to the second exchanger is achieved by the hot water which in turn is produced using the steam resulting from the burned biogas. The produced biogas collected from the top of the reactor is guided to a splitter where it separates into two parts. The splitter solution was adopted because the analysis performed suggested that both burner and MGT are required in order to meet the existing standards and requirements of the plant such as the biogas production ability and the steam consumption.

Hence, a part of the biogas (215 kg/h) is directed to the existing burner and the remaining amount (57.7 kg/h) of the biogas is directed to the MGT combustor. The amount of the biogas produced from anaerobic treatment is sufficient to feed both systems. In the MGT system the inlet air is compressed and then preheated in the recuperator using heat from the turbine exhaust. The biogas is burned with compressed and heated air in the combustion chamber and the resulting hot gases expand through the turbine. Mixing of these gases with the gases from the existing burner occurs just before entering the steam boiler and finally the mixed stream is exhausted to the environment.

In order to study the efficiency of this CW wastewater treatment system producing biogas and moreover heat and electricity, a simulation model is developed using the EES software. This software offers the possibility to calculate the thermodynamic properties required on the basis of the National Aeronautics and Space Administration gas properties data [11]. A sample of the basic equations used for the modeling of the system is given below.

Biogas potential that was evaluated through COD, according to the specific rate, for the calculation of CH_4 production is equal to 0.4 $m^3CH_4/kgCOD_{removed}$ [6]. Thus, the volumetric flow of methane is given by:

$$\dot{Q}_{CH_4} = \dot{Q}_{whey} \times COD_{content} \times COD_{content\text{-}efficiency} \times 0.4\frac{m^3CH_4}{kg\,COD_{removed}} \quad (1)$$

The treated whey exits the reactor with a COD of 1,200 mg/L (corresponds to 98% COD removal efficiency). The CH_4 content in biogas is 60% and the rest is CO_2. The mass flow (m) of the biogas calculated based on the densities of CH_4 and CO_2 at the corresponding state of the system (exit of the reactor) equal to 272.7 kg/h [6].

For the modeling of the heat exchangers the heat from the hot stream is assumed to be transferred completely to the cold stream:

$$\dot{m}_{\text{hot}}\left(h_{\text{hot,inlet}} - h_{\text{hot,outlet}}\right) = \dot{m}_{\text{cold}}\left(h_{\text{cold,outlet}} - h_{\text{cold,inlet}}\right) \quad (2)$$

For the modeling of the mixer of the system, the conservation of mass and energy is expressed by the following equations:

$$\sum \dot{m}_{\text{inlet}} - \dot{m}_{\text{outlet}} = 0 \quad \text{and} \quad \sum \dot{m}_{\text{inlet}} h_{\text{inlet}} - \dot{m}_{\text{outlet}} h_{\text{outlet}} = 0 \quad (3)$$

During the calculations, the pressure losses in the system have been taken into account and are computed by the following equation:

$$\frac{\Delta P}{\rho} = f \times \left(\frac{2 \times L}{D}\right) \times \left(\frac{4 \times Q}{\pi \times D^2}\right)^2 \quad (4)$$

where the Reynolds number is given by:

$$\text{Re} = \frac{u \times D}{v} \quad (5)$$

and the friction factor calculation (Colebrook Equation) by:

$$\frac{1}{\sqrt{f}} = -2 \times \ log\left(\frac{\frac{k_s}{D}}{3.7} + \frac{2.51}{\text{Re} \times \sqrt{f}}\right) \quad (6)$$

The isentropic efficiencies for the biogas and air compressors are defined as follows:

$$n_{\text{sc}} = \frac{h_{\text{outlet,isentropic}} - h_{\text{inlet}}}{h_{\text{outlet}} - h_{\text{inlet}}} \quad (7)$$

The combustion equation of the biogas is described by the following chemical reaction:

$$\lambda \times [0.6CH_4 + 0.4CO_2] + [0.7748N_2 + 0.2059O_2 + 0.0003CO_2 + 0.019H_2O] \rightarrow (1+\lambda)[n_{N_2}N_2 + n_{O_2}O_2 + n_{CO_2}CO_2 + n_{H_2O}H_2O] \quad (8)$$

where the molar fractions of each component in the products can be calculated as a function of λ and are equal to:

$$n_{N_2} = \frac{0.7748}{1+\lambda} \quad (9)$$

$$n_{CO_2} = \frac{0.0003+\lambda}{1+\lambda} \quad (10)$$

$$n_{H_2O} = \frac{0.019 + 1.2 \times \lambda}{1+\lambda} \quad (11)$$

$$n_{O_2} = \frac{0.2059 - 1.2 \times \lambda}{1+\lambda} \quad (12)$$

The heat loses, from the burner and the combustion chamber are considered equal to 2% of the low heating value (LHV) of the biogas. The energy conservation equation becomes:

$$-0.02 \times \lambda \times \text{LHV} + \overline{h_{\text{air}}} + \lambda \times \overline{h_{\text{biogas}}} - (\lambda+1) \times \overline{h_{\text{gases}}} = 0 \quad (13)$$

The MGT operates with a typical recuperated Brayton cycle.

For the turbine, the isentropic efficiency and the energy balance are given by:

$$n_{\text{ST}} = \frac{h_{\text{outlet}} - h_{\text{inlet}}}{h_{\text{outlet,isentropic}} - h_{\text{inlet}}} \quad (14)$$

$$-\dot{W}_{\text{MGT}} + \frac{\dot{m}_{\text{air}}}{\text{MB}_{\text{air}}} \times \left(h_{\text{aircompressor,outlet}} - h_{\text{aircompressor,inlet}}\right) + \frac{\dot{m}_{\text{gases}}}{\text{MB}_{\text{gases}}} \times \left(h_{\text{gasesturbine,outlet}} - h_{\text{gasesturbine,inlet}}\right) = 0 \quad (15)$$

The physical, chemical, and total exergy for each state of the system have been calculated by the following functions (21)–(28), respectively:

$$E^{\text{PH}} = \dot{m} \times [(\bar{h} - \overline{h_0}) + P_0(\bar{s} - \overline{s_0})] \quad (16)$$

$$E^{\text{CH}} = \dot{m} \times \sum x_k \times \bar{e}_k^{\text{CH}} + R \times T_0 \times \sum x_k \times \ln(x_k) \quad (17)$$

$$E_{\text{total}} = E^{\text{PH}} + E^{\text{CH}} \quad (18)$$

The exergy balance for steady state, and taking no heat losses into account, is given by the following balance equation:

$$\sum \dot{m}_{\text{inlet}} \times \bar{e}_{\text{inlet}} - \sum \dot{m}_{\text{outlet}} \times \bar{e}_{\text{outlet}} - \dot{E}_{\text{D}} - \dot{W}_{\text{MGT}} = 0 \tag{19}$$

where subscripts inlet and outlet are the specific exergy of control volume inlet and outlet flow and $\dot{E}_{\text{D}}$ is the exergy destruction.

The total exergy efficiency of the system is given by:

$$\varepsilon_{\text{system}} = \frac{\dot{E}_{\text{steamtofactory}} - \dot{E}_{\text{condensatefromfactory}} + \dot{W}_{\text{total,net}}}{\dot{E}_{\text{untreatedCW}} + \dot{E}_{\text{air,turbine}} + \dot{E}_{\text{air,burner}} + \dot{E}_{\text{water}}} \tag{20}$$

where

$$\dot{W}_{\text{total,net}} = \dot{W}_{\text{total,spend}} + \dot{W}_{\text{MGT}} \tag{21}$$

$$\dot{W}_{\text{total,spend}} = \sum \dot{W}_{\text{pumps}} + \sum \dot{W}_{\text{compr}} \tag{22}$$

$$\dot{W}_{\text{MGT}} = \dot{W}_{\text{sc,biogas,turb}} + \dot{W}_{\text{turb}} \tag{23}$$

For the economic analysis, the NPV calculated as the difference of the net cash flows and the investment capital is given by the following equation:

$$\text{NPV} = \sum \frac{\text{NCF}}{(1+i)^t} - \text{TCI} \tag{24}$$

where
TCI total capital investment (total cost of the system of microgas turbine [12])
NCF net cash flow
i discount rate or rate of return
t year

The company is going to take an extra loan (as it has already got a loan for the existing system [6]) from a bank with an interest rate of 7% to acquire the microturbine unit. It is also considered that the company has not received any grant for the extension of the existing plant. The annual amount of the installment can be calculated from the following equation:

$$\text{AD} = \frac{\varepsilon(1+\varepsilon)^v}{(1+\varepsilon)^v - 1} K \tag{25}$$

where
ε interest rate
v number of years for the full payment of the loan
K loan capital

The extra loan will be paid back in seven years. It is considered that the microturbine is installed to the existing system after four year of its operation (2013). The period of seven years was chosen in order that the company pays back together the two loans (for the existing system [6] and its extension) in the year of 2020. The installments will be constant over these years.

3. Results and discussion

Due to the system operation on an actual scale, the choice of a suitable MGT is not a trivial task. This means that it must be taken into account the limitations, standards, and requirements of the existing system as they have determined previously [6]. The most important requirements among the others are the amount of the biogas produced (272.7 kg/h) and the steam for factory needs (~1,560 kg/h), which have to be satisfied. Moreover, the aim of this study is the matching of the existing system with a commercially available MGT. The sizing of the MGT is a very important issue in order to give realistic results. For this reason, the authors, based on the performance data from commercially available MGTs, investigated the matching of various MGTs with the existing system. Five types were examined: C30 and C60 manufactured from Capstone Turbine Corp, the Parallon 75 kW, the T100 from Turbec [13], and the MT250 from Ingersoll Rand [12,14]. The aim is not only to satisfy the requirements of the existing system but also the specifications of the MGT.

In each test of the analysis, the pressure ratio, the turbine inlet temperature, the compressor, and the turbine isentropic efficiencies are considered as data input to the model. The validation of each testing system was carried out by checking the values resulted from various parameters such as the steam mass flow for factory energy needs, the electricity capacity, the turbine exit temperature, the exhaust gas temperature, and the temperature of the compressed air. The results indicated that although the higher power-rated MGT lead to high electricity power production, it reduces considerably the amount of the steam produced and thus the plant requirements are not met. On the other hand, the lower electricity capacity MGTs leads to excess steam produced while the electricity generated is quite low (Table 1). Through the analysis the T100 was identified as the most suitable MGT.

Table 1
Electricity power and steam production of various MGT sizes

Microturbine	Biogas guided to MGT (kg/h)	Electricity power production (kW)	Amount of steam produced (kg/h)
C30	18.7	30.12	1,701.4
C60	36.7	59.14	1,644.2
Parallon 75	42.7	74.60	1,617.1
T100	57.7	100.8	1,566.6
MT250	151.7	250.17	1,241.8

This recuperated gas turbine produces 100 kW of electrical power with 30 ± 1% efficiency at ISO conditions with gas booster. It constitutes an excellent solution for the extension of the existing system which generates a significant amount of electricity, considering at the same time the constraints referred previously.

Based on the analysis performed for the MGT sizing, it is concluded that the resulting system is quite marginal without any alternative solution in terms of the MGT selection. The values of the T100 MGT parameters used as input to the model are shown in Table 2.

The results for this microturbine cooperation with the existing system presented in Table 3 are in good agreement with the expected performance parameters.

In order to carry out the exergetic analysis of the system the following assumptions have been made during this study:

(1) The reference environment is considered to be at 1.013 bar and 25˚C.
(2) Ideal-gas principles apply for the air, combustion products, and biogas.
(3) Whey which is in liquid form (untreated, recirculated, or treated) is incompressible.
(4) The combustion reactions are complete.
(5) The only heat losses in the system are from the burner and combustion chamber.
(6) In the steam boiler are considered no heat losses.
(7) The calculation of the thermodynamic properties (enthalpy, entropy, pressure, etc.) at each state is performed with equations used for incompressible fluid and mixtures of ideal gases.
(8) The exergetic analyses are made on the LHV of biogas.
(9) The basic molar composition of air consists of 77.48% N_2, 20.59% O_2, 0.03% CO_2, and 1.90% H_2O while the other gases (argon, carbon monoxide, etc.) are assumed to be negligible.

The thermodynamic properties (enthalpy and entropy) and the exergy efficiency and destruction at all states of the system as presented in Fig. 1 have been calculated.

The exergy destruction for each component of the system as percentage of total exergy destructed is shown in Fig. 2. The source of exergy destructions (or irreversibility) in the combustion chamber and burner are the chemical reactions and thermal losses, respectively. The high exergy destruction in the steam boiler is due to the large temperature difference between the input and the output exhausts. As it can be seen in Fig. 2, the greatest exergy losses are observed in the steam boiler, the burner, and the combustion chamber the sum of which reaches to 84% of the total exergy destruction of the system. The exergy destructions in the heat exchanger as well as in the preheater are low due to the low temperature difference between the hot and cold fluid.

The extension of the system has positive effects since the exergetic efficiency is now increased significantly (~30%), compared to the existing one (24%). The increase in exergetic efficiency is due to the

Table 2
Microturbine model parameters

Name	Parameters	Values
Microturbine efficiency	n_{MGT}	0.83
Compressor efficiency	n_{SC}	0.78
Air temperature at the output of preheater (K)	T13	900
Gases temperature of the MGT combustion chamber (K)	T28	1,223
Compressor pressure ratio	PRc	4.5

Table 3
Validation of the matching performance of the MGT with the existing system

Name	Manufacturer [13]	Calculated
Electricity capacity (kW)	100	100.8
GT exhaust temperature (K)	543	542.44
Turbine exhaust gas (K)	923	924.34
Compressed air (K)	487.15	497.37
Steam production (kg/h)	1,560	1,566

reduction of the exergy losses in the boiler and the direct work production.

For the economic analysis an adaptation of the previously existing investment [6] is presented. The analysis is based on the NPV method and the following assumptions.

(1) The operation of the anaerobic treatment is 270 d per year or 6,480 h per year.
(2) The maintenance cost of the MGT is assumed to increase annually by 3%.
(3) The present value of the sold electricity to the network is 0.253 €/kW and it is assumed invariant according to Government Gazette 85/A/04.06.2010.
(4) The annual increase rate of the consumable cost (such as soda which is used for the pH regulation into the reactor) is 3%.
(5) Electricity consumption: it is the cost for the operation of pumps and compressors. The total power of these equipment is 21.55 kW and the cost electricity is 0.08 €/kWh. The electricity cost is assumed to increase annually by 7%.

The incoming cash results from natural gas saving and from savings in electricity which is the income from selling the surplus electricity to the network. The incomings of the extended system are increased significantly compared to those of the existing system due

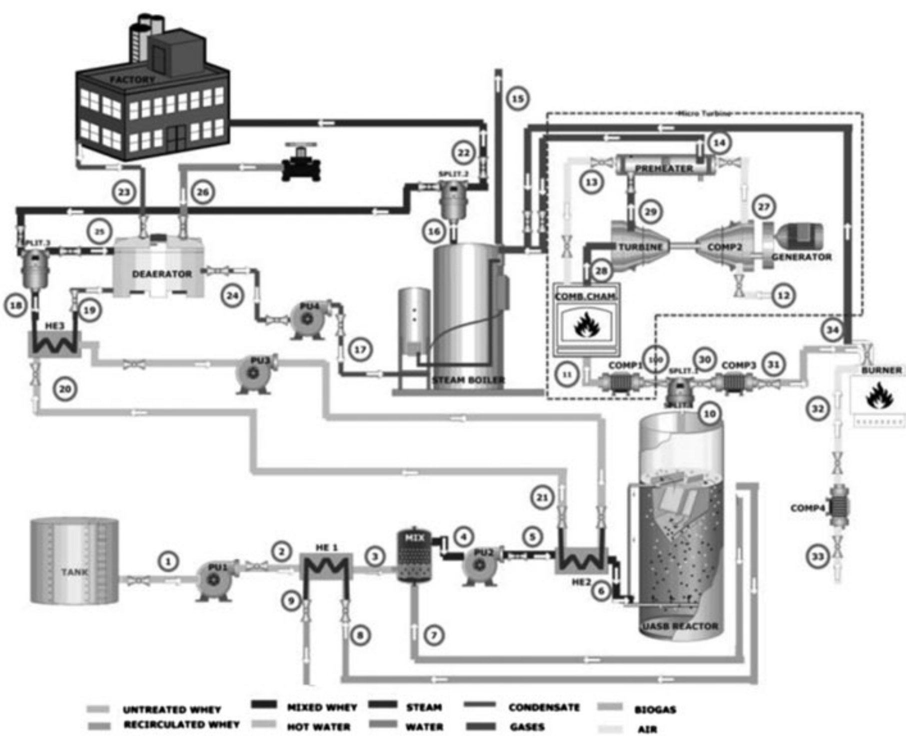

Fig. 1. Flow chart of the system.

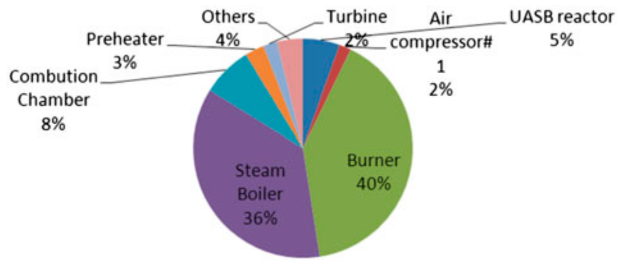

Fig. 2. Exergy destruction in percentage of total exergy destructed.

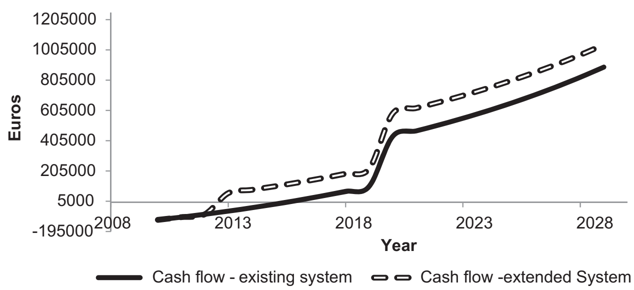

Fig. 3. Cash flows for existing and extended system.

to the savings in electricity. The savings for the first year of the MGT T100 incorporation to the existing system are considerable and are calculated to be 550,000 euro approximately. A significant increase of cash flow in comparison with existing investment is obtained as seen in Fig. 3.

The NPV of the extended system is calculated about 1,760,000 considerably higher (almost double) than the one of the existing system (~648,000). Therefore, the economic analysis results show that the extension of the system is a viable investment.

4. Conclusions

In the present paper, an analysis of a cogeneration system for electricity and heat production through AD treatment of whey wastewater was carried out. More specifically, a study concerning the extension of an existing steam generation system through a microturbine for covering also the electrical needs of the plant was presented. The selection of the suitable MGT for matching with the existing system was not a trivial task. The limitations and the requirements of the existing system had to be satisfied along with the specifications and technical data of the MGT, in order to obtain a realistic system. The extended system considered was studied through the development of an appropriate simulation model validated with available data. Based on the analysis performed for the MGT sizing, it was also concluded that the resulting system is quite marginal without any alternative solution in terms of the MGT selection. The results obtained have shown that it is possible to obtain 64,800 kWh per year electric energy along with 1,570 kg/h, approximately, steam production.

The results of the exergy analysis revealed that the exergetic efficiency of the extended system is significantly increased compared to the existing one. From the economic analysis was revealed that this investment is profitable for the company, with high savings and incomes from the first year of its operation. Eventually the anaerobic treatment of high strength waste such as CW for biogas production and its further use for cogeneration of electricity and heat is a sustainable way for the factory to treat the whey it produces covering its energy needs.

Another economically profitable solution for the factory could constitute the use of the whole biogas to produce only electricity due to the present high value of the sold electricity to the network. In this case, the electricity production is calculated around to 1.5 MW.

In the available literature, the numbers of industrial-scale existing operating AD systems with CHP unit, especially in dairy industries, are limited. However, the increasingly stringent regulations for the wastewater disposal and the need to cover energy requirements necessitate the continuous improvement of technology and study of such systems. The methodology presented could be exploited in similar studies for the evaluation of the effects of incorporating MGTs with other waste treatment plants.

References

[1] R. Ben-Hassan, A. Ghaly, Continuous propagation of Kluyveromyces fragilis in cheese whey for pollution potential reduction, Appl. Biochem. Biotechnol. 47 (1994) 89–105.

[2] A. Saddoud, I. Hassaïri, S. Sayadi, Anaerobic membrane reactor with phase separation for the treatment of cheese whey, Bioresour. Technol. 98 (2007) 2102–2108.

[3] T.H. Ergüder, U. Tezel, E. Güven, G.N. Demirer, Anaerobic biotransformation and methane generation potential of cheese whey in batch and UASB reactors, Waste Manage. 21 (2001) 643–650.

[4] A. Wellinger, J. Murphy, D. Baxter (Eds.), The Biogas Handbook Science, Production and Applications. Cambridge: Woodhead Publishing Limited, 2013. Available from: http://www.elsevier.com/books/the-biogas-handbook/wellinger/978-0-85709-498-8.

[5] P.A. García, J.L. Rico, F. Fdz-Polanco, Anaerobic treatment of cheese whey in a two-phase uasb reactor, Environ. Technol. 12 (1991) 355–362.

[6] F.X. Wildenauer, J. Winter, Anaerobic digestion of high-strength acidic whey in a pH-controlled up-flow fixed film loop reactor, Appl. Microbiol. Biotechnol. 22 (1985) 367–372.

[7] M.S. Switzenbaum, S.C. Danskin, Anaerobic expanded bed treatment of whey, Agric. Wastes 4 (1982) 411–426.

[8] A.A. Chatzipaschali, A.G. Stamatis, Biotechnological utilization with a focus on anaerobic treatment of cheese whey: Current status and prospects, Energies 5 (2012) 3492–3525.

[9] T. Spachos, A. Stamatis, Thermal analysis and optimization of an anaerobic treatment system of whey, Renewable Energy 36 (2011) 2097–2105.

[10] C.X. Cáceres, R.E. Cáceres, D. Hein, M.G. Molina, J.M. Pia, Biogas production from grape pomace: Thermodynamic model of the process and dynamic model of the power generation system, Int. J. Hydrogen Energy 37 (2012) 10111–10117.

[11] Engineering Equation Solver. Available from: http://www.fchart.com/ees/ (14/12/2012).

[12] Technology Characterization: Microturbines, 2008. Available from: http://www.epa.gov/chp/documents/catalog_chptech_microturbines.pdf.

[13] D.P. Bakalis, A.G. Stamatis, Incorporating available micro gas turbines and fuel cell: Matching considerations and performance evaluation, Appl. Energy 103 (2013) 607–617.

[14] M.Y. El-Sharkh, N.S. Sisworahardjo, M. Uzunoglu, O. Onar, M.S. Alam, Dynamic behavior of PEM fuel cell and microturbine power plants, J. Power Sources 164 (2007) 315–321.