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Thermal analysis and optimization of an anaerobic treatment system of whey

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A R T I C L E I N F O

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A B S T R A C T

The whey produced during cheese and cream cheese making process is one of the most important environmental problems dairy industries are facing, due to its high organic load. Anaerobic treatment seems to be a promising solution for this problem, since it not only reduces greatly the organic load but it also produces biogas, which can be then burnt. It is the scope of this study to perform an exergetic and economic analysis of an anaerobic treatment system of whey accompanied by the production of steam resulting from the burning of biogas. The system analyzed extends from the storage of whey, up to the disposal of the treated effluent from the anaerobic reactor, and the exit of the steam to be used in the plant. The exergy analysis is performed treating the system as a steam production plant, while the economic analysis, which is performed using the Net Present Value (NPV) method, is performed treating the system as a natural gas production plant. The exergy efficiency and NPV calculations are followed by a sensitivity analysis and an optimization with respect to some of the parameters used. Moreover, the exergy efficiency and NPV are calculated for three scenarios. The results indicate that the anaerobic treatment of high strength waste such as whey is a sustainable investment, at least for a substantial volume of whey.

1. Introduction

The ongoing depletion of fossil fuels followed by its economic and climate consequences and the environmental awareness of nowadays make more urgent than ever the need to shift to new environmental friendly technologies. These technologies will take advantage of any renewable energy source to produce energy and will treat waste in a less costly way, in terms of energy consumption and environmental impact. In this perspective high strength waste which used to trouble the producer become a potential fuel producer.

In the same way, waste such as whey produced in dairy industries which carries a high organic load in terms of Chemical Oxygen Demand (COD), instead of requiring a lot of energy to be treated in an aerobic plant, can produce energy itself. This can be achieved using the anaerobic treatment technology, which not only removes a great amount of COD but also produces biogas, a mixture of methane and carbon dioxide, which can then be used to produce electricity, steam or both.

The work that has been done so far in the anaerobic treatment of whey, have studied topics such as the impact of temperature under which the anaerobic treatment takes place [1,2], or the hydraulic retention time (HRT) [3,4], in COD removal efficiencies and the methane content in biogas. The HRT as well as the COD of the effluent also affect the rate of methane (CH_4) produced per kg of COD removed which seems to vary [5,6]. The type of the anaerobic reactor used plays also an important role in the anaerobic process, and some works have been done on Upflow Anaerobic Sludge Blanket (UASB) reactors, which is the type of reactor used in this study also [7,8]. The exergy analysis of anaerobic treatment of waste has been covered [9], but it does not refer to whey.

It is the scope of this study to perform an exergy and economic analysis for an anaerobic treatment system installed in one of the biggest dairy industries in Greece. The boundaries system examined include the steam delivered to the plant from the burning of the biogas produced. The anaerobic plant has been designed to treat 150 m^3/day of whey, produced with the use of ultra-filtration (UF) membranes. The analysis performed is followed by a sensitivity analysis and optimization relative to some of the parameters used. Also, the effect of three different scenarios, concerning possible improvements, to the exergy efficiency of the system and the NPV are presented.

2. Whey and anaerobic treatment

A great part of the milk used for cheese making is leaving the process as whey. This whey can be further used for the production of a small amount of cream cheese relative to the whey leaving the process, which is not used further for human consumption. Whey is

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Nomenclature

PU1,…, PU4	Pump1,…, Pump4
HE1,…, HE3	Heat exchanger 1,…, Heat exchanger 3
COMP1	Biogas compressor
COMP2	air compressor
T	temperature
P	pressure
$\bar{h}$	specific enthalpy
H	Enthalpy
$\bar{s}$	specific entropy
S	entropy
$\bar{e}$	specific exergy
$\dot{E}$	exergy
$\dot{m}$	mass flow
$\dot{Q}$	volumetric flow
X	mass fraction
$\bar{v}$	specific volume
N	moles
R	gas constant
D	density
F	friction factor
Re	Reynolds number
k_s	roughness of pipe
D	pipe diameter
U	mean fluid velocity
v	kinematic viscosity
L	equivalent length
TOC	Total Organic Carbon
M	molar mass
A_r	atomic weight
LHV	low heating value
NPV	Net Present Value
NCF	Net Cash Flow
TCI	Total Cost of Investment
i	discount rate or rate of return
t	year, from 1 to 20
AD	amortization dose
ε	interest rate
ν	number of years for the full payment of the loan
K	loan capital

Subscript

H_2O	Water
s	solute-for untreated whey the solute is the lactose
f	saturated liquid phase
sat	saturated
k	k-th component of a mixture
0	reference state
1,2,…,26	number of state
air	air
biogas	biogas
gases	gases
P1,…,P4	Pump 1,…,4
C1, C2	Biogas compressor, air compressor

Superscript

PH	physical
CH	chemical

also produced during strained yoghurt production. The characteristics of whey depend on factors such as the type of milk used, i.e. if it comes from sheep, goat or cow milk, and the period of the year, but they can be approximated by the characteristics given in Table 1.

The need to minimize the production cost has introduced the ultra-filtration (UF) membranes in the cheese and cream cheese making processes. The UF are used to concentrate milk or whey before cheese or cream cheese production respectively. The diameter of the pores of the membranes is such that it allows molecules of water, salts, sugars and low molecular weight compounds to pass, but blocks molecules of proteins and fats, as it is also shown in Fig. 1 [10]. Thus, the permeate taken, which is whey, consists mainly of water and lactose, while protein content is minimized to less than 0.1% [4].

The plant examined in this paper produces whey resulting from UF membranes. It thus can be considered for the analysis that whey consists only of water by 95% and lactose ($C_{12}H_{22}O_{11}$) by 5%.

The problem for the dairy industry discussed is that whey has a high organic load, which if measured in terms of COD equals to 60.000 mg/lit, when the rest of the wastewater have a COD equal to 4.000 mg/lit. So, handling of it is quite difficult, since the prospect of treating it in the aerobic plant would require for a lot of space and electricity. The alternative ways of treating it will have to do with disposal to farmers for animal feeding or to other plants. The first alternative cannot solve the problem completely, since there are not always enough farmers, while the second burdens the company with costs such as transport and labor. A sustainable solution to this problem seems to be the anaerobic treatment of whey, since it not only reduces greatly the COD but also produces biogas.

Anaerobic treatment is a series of processes in which microorganisms break down biodegradable material in the absence of oxygen, used for industrial or domestic purposes to manage waste and to release biogas, a mixture of CH_4 and carbon dioxide (CO_2) [11]. It is mainly used for high strength waste such as whey.

The effluents of the anaerobic treatment are biogas and a treated flow with a substantially less organic load. The greatest advantages of this way of treatment is that it takes place in the absence of oxygen, which minimizes the electricity consumption, and that it produces biogas, which can be used to produce energy. It is calculated that 90–95% of the carbon contained in the raw effluent is converted to biogas, as it can also been shown in Fig. 2 [12], while the rest goes to the treated effluent and the anaerobic bacteria-microorganisms.

The anaerobic treatment takes place in four stages [11]: Hydrolysis, Acidogenesis, Acetogenesis and Methanogenesis. Each of the stage involves different bacteria [11,12].

The processes-stages take place in an anaerobic reactor, which in this case is of type UASB. The choice was based on the fact that UASB is a reactor where high organic removal efficiencies are achieved with quite low hydraulic retention time of the waste in the reactor [13,14]. Two reactors have been installed in the plant examined and their shape is cylindrical. The entrance of the untreated whey is from the bottom of the reactor, while the outlet

Table 1
Composition and characteristics of whey resulting from the white cheese making process.

Constituent	Percentage (%)
Water	94
Protein	0.8–1.0
Lactose	4.5–5.0
Fat	<0.1
Minerals	<0.1
pH	4.5–5

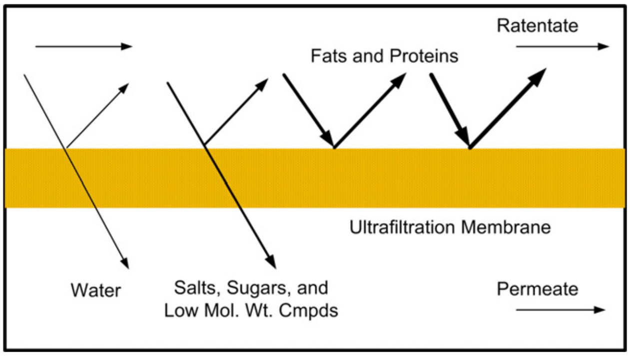

Fig. 1. Ultra-filtration schematic process.

of biogas and the treated flow are at the top. The bacteria in the reactor are mesophilic, which means that the temperature inside the reactor is kept at 35 °C.

3. System description

The filtered whey is collected at ambient conditions in three stainless steel tanks, each of 125 m^3, which serve as buffer. Then, it is pumped with the use of a centrifugal pump at a constant flow of 6,25 m^3/hr to the reactor. The untreated whey is heated in the first heat exchanger from the treated whey which exits the reactor, and then it is mixed with a recirculated whey which is taken from the top of the reactor. Because the recirculated whey is taken very close to the outlet of the treated whey it can be assumed that it has the same characteristics with it. The mixed flow is then pumped to the reactor where it enters after it passes a second heat exchanger where it is heated to the desired temperature of 35 °C. The heating to the second reactor is achieved using hot water which in turn is produced with the use of steam resulting from the burning of biogas. The biogas produced in the reactor is collected from the top and is compressed to the burner where it is burned with ambient air. The gases are directed to a steam boiler and are then disposed at a mean temperature of 200 °C. The steam produced in the steam boiler is directed to the plant in order to cover part of its thermal needs. A small part of the steam produced is use to heat up the hot water needed in the second heat exchanger, and to heat up the condensate in the deaerator to the temperature of 102 °C. Because of the losses taking place in the plant, the condensates returning to the deaerator are not equal to the steam delivered to the plant. The rest of the quantity needed is covered with the addition of fresh water.

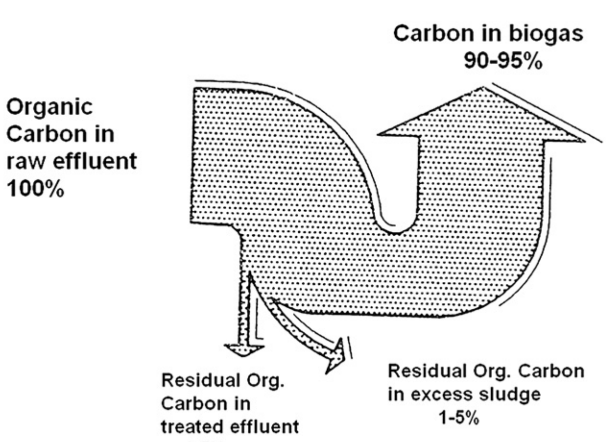

Fig. 2. Mass balance of carbon in anaerobic treatment of organic components.

The flow chart of the system is shown in Fig. 3. The values given on the chart are known.

4. Modeling

4.1. Exergy analysis

Firstly, it should be stated that the exergy analysis is performed treating the system as a steam production plant. Thus, for the calculation of the exergy efficiency of the system, the exergy of the product is the exergy of the steam delivered to the plant minus the exergy of the condensate returning from it.

The reference state of the system corresponds to temperature $T_0 = 298.15$ K and pressure $P_0 = 1.013$ bar.

As already mentioned untreated whey is assumed to consist only of water (95%) and lactose (5%). The solid part of whey will be called solute. Thus, the solute of the untreated whey is lactose.

Whey which is in liquid form, either it is untreated, recirculated or treated, is assumed to be incompressible, while air, biogas and gases are treated as mixtures of ideal gases.

The only heat losses in the system are assumed to take place in the burner.

The calculation of the thermodynamic properties, such as pressure, enthalpy and entropy, at each state is performed with the equations used for incompressible fluid and mixtures of ideal gases.

Moreover, the total exergy at each state is a sum of the physical and chemical exergy, thus omitting any other types of exergy, such as kinetic and dynamic since they are negligible.

The equations used for the calculation of physical properties, exergy, exergy efficiency and destruction as well as the pressure losses are given in Appendix A.

The pipes used in the plant are of stainless steel.

The pumps installed as well as the compressors of biogas and air, are driven by inverters. In order to find their power consumption, data concerning the flow and the head, for different rotational speed and powers are used for different flows and heads. Thus, for any given volumetric flow and head, the power consumed, the efficiency and the frequency are calculated, with the use of double interpolation.

For the modeling of the heat exchangers, the heat lost from the hot stream is transferred completely to the cold stream, considering no losses, i.e.:

$$\dot{m}_{hot} \cdot \left(\overline{h}_{hot,inlet} - \overline{h}_{hot,outlet}\right) = \dot{m}_{cold} \cdot \left(\overline{h}_{cold,outlet} - \overline{h}_{cold,inlet}\right) \tag{1}$$

The mixing of the untreated and the recirculated whey, results to flow given in state 4 which has the same pressure as flows 3 and 7, while temperature T_4 is given by:

$$T_4 = \frac{\dot{m}_3 \cdot T_3 + \dot{m}_7 \cdot T_7}{\dot{m}_3 + \dot{m}_7} \tag{2}$$

Moreover, the mass fraction of the k-th component in the mixture is given by:

$$x_{k,4} = \frac{\dot{m}_3 \cdot x_{k,3} + \dot{m}_7 \cdot x_{k,7}}{\dot{m}_3 + \dot{m}_7} \tag{3}$$

The specific rate for the calculation of CH_4 production is equal to 0.4 m^3 CH_4/kgCOD$_{removed}$ [5]. Thus, the volumetric flow of methane will be:

$$\dot{Q}_{10,CH4} = \dot{Q}_1 \times COD_{content} \times COD_{removal-efficiency} \times \frac{0.4m3CH4}{kgCOD_{removed}} \tag{4}$$

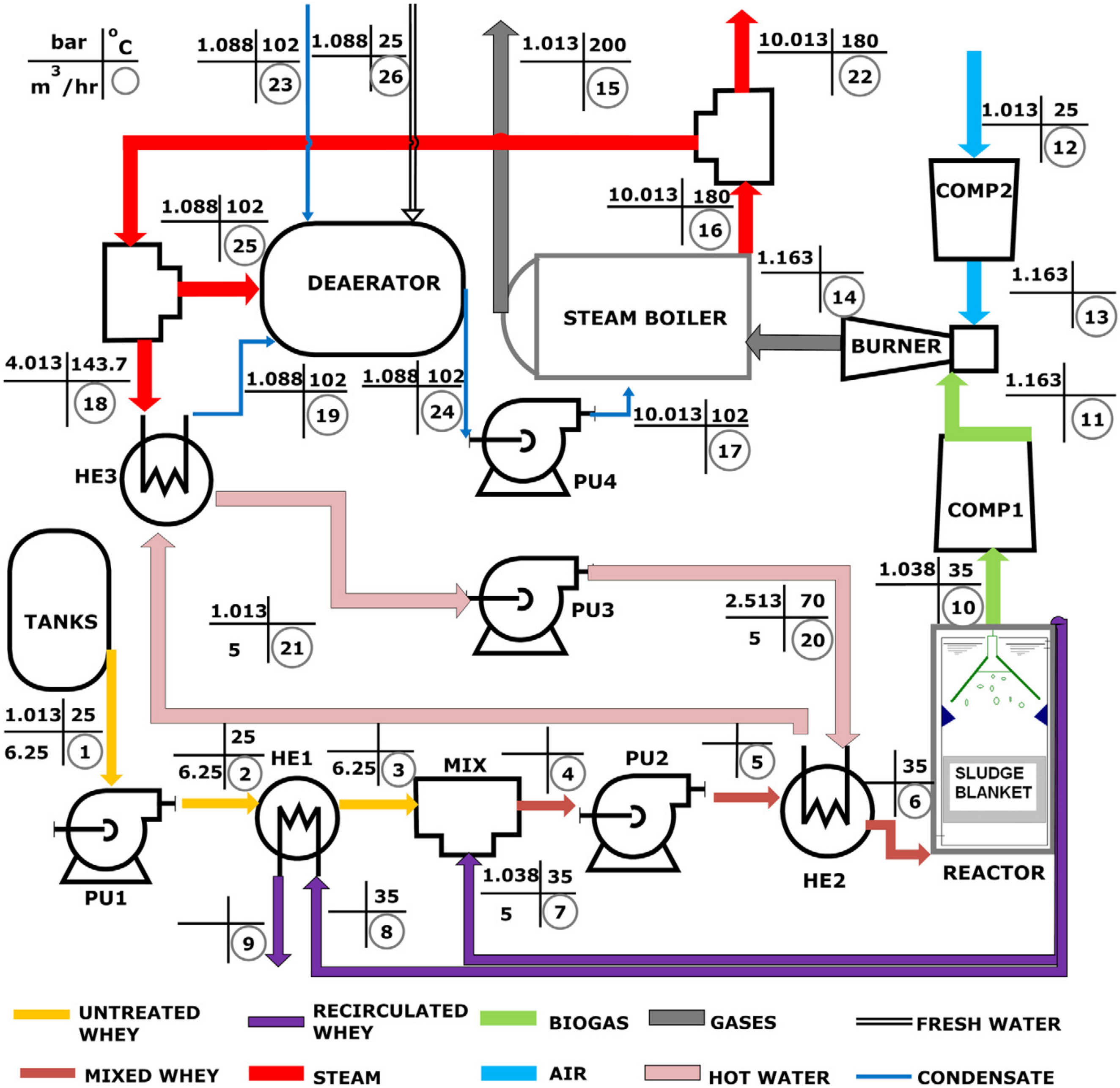

Fig. 3. Flow chart of the system examined.

The treated whey exits the reactor with a COD of 1.200 mg/lit, which corresponds to a COD removal efficiency of 98%. The CH_4 content in biogas is 60% and the rest is CO_2. So, given the densities of CH_4 and CO_2 at state 10, the mass flow of biogas can be calculated.

The *TOC* of the inlet flow and the biogas can be calculated by equations:

$$TOC_1 = \frac{\dot{m}_1 \cdot x_{s,1}}{MB_{s,1}} \times A_{r,C} \times (\text{Carbon Atmos in Lactose}) \tag{5}$$

$$TOC_{10} = \frac{\dot{m}_{CH4,10}}{M_{CH4}} \cdot (\text{Caron atoms in } CH_4) + \frac{\dot{m}_{CO2}}{M_{CO2}} \cdot (\text{Caron atoms in } CO_2) \tag{6}$$

From the equations above, it can be found that $TOC_{10}/TOC_1 = 90\%$. The rest of *TOC* goes to the biomass and the treated flow, and, according to Fig. 2, it is assumed that 5% of TOC_1 goes to the treated flow and 5% to the biomass.

According to Tai et al. [15] there is a relation between *TOC*, chemical exergy and free energy of organic matter in wastewater. So, the chemical exergy and the free energy of the treated flow will be reduced by 95% relative to these of the untreated whey. It is assumed that the reduction of the free energy of the treated flow by 95% corresponds to the reduction of enthalpy and entropy of the treated flow by the same amount, 95%. Thus:

$$\overline{h}_{s,8} = \overline{h}_{s,7} = 0.05 \cdot \overline{h}_{s,1} \tag{7}$$

$$\overline{s}_{s,8} = \overline{s}_{s,7} = 0.05 \cdot \overline{s}_{s,1} \tag{8}$$

$$\bar{e}_{s,8}^{CH} = \bar{e}_{s,7}^{CH} = 0.05 \cdot \bar{e}_{s,1}^{CH} \tag{9}$$

It is further assumed that the decomposition of lactose is approximated by the reaction:

$$C_{12}H_{22}O_{11} \rightarrow A \cdot CH_4 + B \cdot CO_2 + C_aH_bO_c \tag{10}$$

Where $C_aH_bO_c$ is the hydrocarbon left in the treated flow. From the reaction above it can be seen that 1 mol of lactose gives 1 mol of $C_aH_bO_c$. So:

$$\frac{\dot{m}_1 \cdot x_{s,1}}{MB_{LACTOSE}} = \frac{\dot{m}_8 \cdot x_{s,8}}{MB_{S,8}} \tag{11}$$

Where $x_{s,8}$ is given by:

$$x_{s,8} = \frac{\dot{m}_{s,8}}{\dot{m}_8} \tag{12}$$

And taking into account that 5% of *TOC* will go to the treated flow and 5% will be consumed by biomass:

$$2 \cdot \dot{m}_{s,8} = \dot{m}_{s,1} - \dot{m}_{10} \tag{13}$$

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

Biogas compressor:

$$n_{sc,biogas} = \frac{h_{11,isentropic} - h_{10}}{h_{11} - h_{10}} \tag{14}$$

Air compressor:

$$n_{sc,air} = \frac{h_{13,isentropic} - h_{12}}{h_{13} - h_{12}} \tag{15}$$

The combustion of biogas is governed by the chemical reaction:

$$\lambda[0.6CH_4 + 0.4CO_2] + [0.7748N_2 + 0.2059O_2 + 0.0003CO_2 + 0.019H_2O] \rightarrow (1+\lambda)[n_{N2}N_2 + n_{O2}O_2 + n_{CO2}CO_2 + n_{H2O}H_2O] \tag{16}$$

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

$$n_{N2} = \frac{0.7748}{1+\lambda} \tag{17}$$

$$n_{CO2} = \frac{0.0003 + \lambda}{1+\lambda} \tag{18}$$

$$n_{H2O} = \frac{0.019 + 1.2 \cdot \lambda}{1+\lambda} \tag{19}$$

$$n_{O2} = \frac{0.2059 - 1.2 \cdot \lambda}{1+\lambda} \tag{20}$$

The molar fraction of O_2 has been measured with the use of a gas analyzer and has been found equal to 0.04. If λ^* corresponds to complete combustion, i.e. $n_{O_2} = 0$, the excess air used for the combustions is given by:

$$ExcessAir = \frac{\lambda^*}{\lambda} \tag{21}$$

The heat losses from the burner are taken equal to 2% of the low heating value of the biogas. Thus, the energy conservation equation for the burner becomes:

$$0 = 0.02 \cdot \lambda \cdot LHV + \bar{h}_{air} + \lambda \cdot \bar{h}_{biogas} - (1+\lambda) \cdot \bar{h}_{gases} \tag{22}$$

The steam boiler is treated as a heat exchanger, in the sense that all the heat from the gases is transferred to condensate for the production of steam, with no heat losses taking place: That is:

$$\dot{m}_{16} \cdot \bar{h}_{16} - \dot{m}_{17} \cdot \bar{h}_{17} = \dot{m}_{14} \cdot \bar{h}_{14} - \dot{m}_{15} \cdot \bar{h}_{15} \tag{23}$$

Where:

$$\dot{m}_{16} = \dot{m}_{17} \tag{24}$$

and

$$\dot{m}_{14} = \dot{m}_{15} \tag{25}$$

The deaerator is used as a feeding tank for the boiler and to keep the feeding water saturated at 20 mbar pressure.

The modeling of the system involves some parameters whose values are either unknown or they change. These parameters are:

- The isentropic efficiency of the biogas and air compressors which are taken equal to 85%,
- The thermal losses of the burner to the environment whose value is given above
- The temperature at which the gases are leaving the steam boiler, which is taken equal to 473.15 K, and
- The quantity of the condensate returning from the plant, which is taken equal to 70% relative to the steam delivered to the plant.

It has been stated that the system is treated as a steam production plant, thus the exergy efficiency is given by:

$$\varepsilon_{system} = \frac{\dot{E}_{product}}{\dot{E}_{fuel}} = \frac{\dot{E}_{22} - \dot{E}_{19}}{\dot{E}_1 + \dot{E}_{12} - (W_{P1} + W_{P2} + W_{P3} + W_{P4} + W_{C1} + W_{C2})} \tag{26}$$

4.2. Economic analysis

The economic analysis is performed using the method of Net Present Value (NPV), which is calculated as the difference of the net cash flows minus the investment capital, and is given by equation:

$$NPV = \sum \frac{NCF}{(1+i)^t} - TCI \tag{27}$$

The sum refers to the number of years that the investment will last.

The incoming cash flow comes from the saving in natural gas. Natural gas is the fuel used by the plant to cover its thermal needs. So, the same amount of steam produced by biogas would have to be produced by natural gas. Thus, it should be noted that for the economic analysis the system is treated as a natural gas production plant.

The Total Capital Investment (*TCI*), is the total cost of the system described. It is the sum costs such as:

- Equipment: Buffer tanks, pumps, heat exchangers, piping, reactor, compressors, burner, boiler, deaerator, biogas buffer tank
- Measuring and sampling devices
- Electrical connections, boards and cables
- Civil works
- Installation

These costs are given in Table 2. It should be noted that the system could be divided in two subsystems. The reason is that the system was executed by more than one supplier who had different cost accounting policies. The first subsystem extends up to the biogas compressor without the buffer tanks, while the second starts form the air compressor and goes up to the steam delivery to the plant. The cost of measuring and sampling devices as well as the cost of the electric equipment and works for the first subsystem are given as a fraction of the equipment cost for the same subsystem. The installation cost for the first subsystem is included in the cost of equipment. For the second subsystem, the installation cost is given as a fraction of the equipment cost, while the measuring devices and electric equipment are included in the cost of the equipment. The TCI of the system is calculated by adding the TCI of the two subsystems plus the civil cost. The analysis used for the calculation of TCI is in consistence with Reference [16].

For the calculation of the NPV the following parameters and costs are taken into account:

- The operation of the anaerobic treatment is 270 days per year, or 6480 h per year.
- Labor cost: Two persons will be employed in the system. The labor cost will increase annually by 3%.
- Consumable cost: It has to do with consumables such as soda which is used for the pH regulation into the reactor. The annual increase rate is 3%.
- 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 of electricity is 0.08 €/kWh. The electricity cost is assumed to increase annually by 7%.
- Maintenance cost: The maintenance cost is divided to three categories:
  - ➢ The maintenance cost for the pumps and the compressors, which is assumed to be equal to 4% of the purchase cost,
  - ➢ The maintenance cost for the measuring, sampling and electronic devices which refers to the devices used in the first subsystem and is assumed to be equal to 2% of the purchase cost, and
  - ➢ The maintenance cost for the rest of the equipment, such as the reactors, the steam boiler, the deaerator, the mixing and separation unit, the heat exchangers, the piping and the valves. This cost is assumed to be equal to 0.5% of the purchase cost.

  The maintenance cost is assumed to increase annually by 3%

- The company is going to loan the money from a bank, with an interest rate of 7%. The annual amount of the installment can be calculated form equation:

$$AD = \frac{\varepsilon \cdot (1+\varepsilon)^{\nu}}{(1+\varepsilon)^{\nu}-1} \cdot K \tag{28}$$

The loan will be paid back in ten years. The installments will be constant over these years.

As already stated the incoming cash flow come from the saving in natural gas. Hence, given the steam produced from the biogas, the natural gas which would be used instead is calculated to almost 157 m^3/hr, and taking into account that the mean cost of natural gas for 2009 was 0.31879 €/m^3, the saving for the first year amounts to 347,587 €. The cost of natural gas over the following years is assumed to increase annually by 7%.

Moreover, the discount rate or rate of return is assumed to be 5%.

Table 2
Data for the calculation of the Total Capital Investment.

	Cost (€)
Subsystem#1	
Pump#1	5,000
Heat Exchanger#1	15,000
Mixing Unit	3,000
Pump#2	5,000
Heat Exchanger#2	15,000
UASB Reactors	440,000
Biogas Compressor	80,000
Rest (Piping, valves and their installation)	237,000
Cost of Equipment (PEC) of Subsystem#1	800,000
Measuring and Sampling devices (6% of PEC)	48,000
Electric works, boards (19% of PEC)	152,000
TCI of Subsystem#1	1,000,000
Subsystem#2	
Air Compressor	5,000
Burner	55,000
Steam Boiler	150,000
Steam separator	2,000
Heat Excanger#3 and Pump#3	5,000
Deaerator	60,000
Pump#4	3,000
Buffer Tanks for whey	120,000
Others (piping, valves, racks)	165,000
Cost of Equipment (PEC) of Subsystem#2	565,000
Installation cost (∼45% of PEC)	254,000
TCI of Subsystem#2	819,000
Civil Cost	250,000
TCI of System	2,069,000

Table 3
Fluid conditions, Mass flow, temperature, pressure, enthalpy, entropy and total exergy at each phase of the system.

State	Fluid Condition	$\dot{m}$ (kg/hr)	T (K)	P (bar)	$\bar{h}$ (kJ/kmol)	$\bar{s}$ (kJ/kmol K)	$\dot{E}$ (kW)
1	Untreated Whey	6341.7	298.15	1.013	-8994	14.862	1526.21
2	Untreated Whey	6341.7	298.15	1.569	-8992	14.862	1526.30
3	Untreated Whey	6341.7	302.15	1.038	-8450	16.675	1526.40
4	Mixture[a]	11333.1	304.79	1.038	-2023	13.375	1579.58
5	Mixture	11333.1	304.79	1.873	-2021	13.374	1579.84
6	Mixture	11333.1	308.15	1.852	-1652	14.579	1581.00
7	Recycled Whey	4991.4	308.15	1.038	2612	9.080	63.65
8	Treated Whey	6046.8	308.15	1.072	2612	9.080	77.11
9	Treated Whey	6046.8	300.58	1.013	2043	7.211	76.02
10	Biogas	272.7	308.15	1.038	-201964	203.721	1387.21
11	Biogas	272.7	317.53	1.163	-201617	203.886	1388.04
12	Air	2052.0	298.15	1.013	-4713	199.130	0.06
13	Air	2052.0	312.15	1.163	-4302	199.328	7.06
14	Gases	2324.7	1860.95	1.163	-30474	265.124	908.95
15	Gases	2324.7	473.15	1.013	-82496	216.358	58.93
16	Steam	1807.6	453.10	10.013	50044	118.647	412.38
17	Condensate	1807.6	375.15	10.013	7714	23.938	19.62
18	Steam	66.8	416.89	4.013	49339	124.224	12.80
19	Condensate	66.8	375.15	1.088	7702	23.951	0.71
20	Hot Water	4985.0	343.15	2.513	5282	17.202	21.56
21	Hot Water	4985.0	335.78	1.013	4724	15.566	16.15
22	Steam	1672.0	453.10	10.013	50044	118.647	381.45
23	Condensate	1170.4	375.12	1.088	7700	23.946	12.41
24	Condensate	1807.6	375.12	1.088	7700	23.946	19.16
25	Steam	68.7	375.12	1.088	48262	132.075	9.55
26	Fresh Water	568.4	298.15	1.088	1889	6.611	0.40

[a] Refers to the mixture of untreated and recirculated whey, coming from flow 3 and 7 respectively.

Table 4
Results for the exergy efficiencies, the exergy destruction and the exergy losses relative to the inlet exergy.

No	Equipment	Exergy efficiency, ε(%)	Exergy destruction (kW)	Exergy destruction relative to inlet exergy (%)	Exergy losses relative to inlet exergy %)
1	Pump#1	31.42	0.20	0.01	
2	Heat Exchanger#1	8.91	0.99	0.06	4.94[b]
3	Mixing[a]	99.34	10.46	0.68	
4	Pump#2	44.92	0.31	0.02	
5	Heat Exchanger#2	21.42	4.25	0.28	
6	UASB reactor	96.65	53.03	3.45	
7	Biogas Compressor	85.88	0.14	0.01	
8	Air compressor	85.62	1.17	0.08	
9	Burner	65.15	486.14	31.60	
10	Steam Boiler	46.21	457.26	29.72	3.83[c]
11	Steam separator	97.92	8.57	0.56	
12	Heat Exchanger#3 and Pump#3	42.69	7.26	0.47	
13	Deaerator	83.09	3.90	0.25	
14	Pump#4	40.55	0.66	0.04	
15	SYSTEM	23.99	1034.36	67.24	8.77

[a] Refers to the mixing of untreated and recirculated whey from states 3 and 7 respectively.
[b] Refers to the disposal of the treated whey-state 9.
[c] Refers to the disposal of the gases-state 15.

5. Results

5.1. Exergy analysis

The mass flow, temperature, pressure, enthalpy, entropy, total exergy and the fluid condition at each state of the system are given in Table 3.

The results of the exergy efficiencies, exergy destructions and exergy losses are shown in Table 4. As it can be seen from the results the exergy efficiency of the system is quite low (23.99%). This is because of the great exergy losses in the burner and the boiler, as they both account for almost 91% of the exergy losses.

Table 6
Range of values of exergy efficiency and NPV calculated for the range of the parameters whose values are either unknown or change.

Parameter	Range of values of the Parameter	Range of values of ε (%)	Range of values of NPV (€)
$n_{sc,air}$	75–85%	23.99–23.99	635,837–648,167
$n_{sc,air}$	75–85%	23.99–23.99	677,906–648,167
P11	1.093–1.313bar	23.99–23.99	652,932–638,058
T15	453.15–493.15 K	24.30–23.68	661,762–634,144
$x_{14,O2}$	2.5–5%	24.16–23.86	703,457–605,544
P16	8.013–11.013bar	24.07–23.95	667,875–633,801

5.2. Economic analysis

The results of the economic analysis are summarized in Table 5, where the NPV is also calculated. The Table shows the incoming cash resulting from the natural gas saving, and the outgoing cash flows resulting from the operational and maintenance costs and the installments paid for a period of ten years. The result reveals that the anaerobic treatment of whey is a profitable and sustainable investment for the company.

5.3. Sensitivity analysis

As already mentioned the values of some parameters are either unknown, change or are able to change. Table 6 provides the range for the exergy efficiency of the system and the NPV for the range of these parameters. From the results, it can be seen that the parameter whose values have a substantial impact on the exergy efficiency is the temperature at which the gases are disposed to the environment while for the NPV the greatest impact is caused by the oxygen content in the gases.

5.4. Optimization

The optimization of the exergy efficiency or the NPV has been performed relative to some of the parameters given in sensitivity

Table 5
Incoming and outgoing flows and *NPV* calculation (in Euros).

Year	Cal. Year	Outgoing Cash Flows							Incoming Cash flow	Cash Flow	Cash Flow Based on Present Value
		Operational Costs			Maintenance Costs			Installments			
		Labor cost	Consumables	Electricity	Pumps-Compressors	Instruments	Other				
0	2009									−2,069,000	−2,069,000
1	2010	70,000	53,000	6,057	6,320	1,000	4,610	294,615	317,829	−117,773	−112,165
2	2011	72,100	54,590	6,482	6,510	1,030	4,748	294,615	340,077	−99,997	−90,700
3	2012	74,263	56,228	6,935	6,705	1,061	4,891	294,615	363,882	−80,815	−69,811
4	2013	76,491	57,915	7,421	6,906	1,093	5,037	294,615	389,354	−60,123	−49,463
5	2014	78,786	59,652	7,940	7,113	1,126	5,189	294,615	416,609	−37,811	−29,626
6	2015	81,149	61,442	8,496	7,327	1,159	5,344	294,615	445,772	−13,760	-10,268
7	2016	83,584	63,285	9,091	7,546	1,194	5,505	294,615	476,976	12,157	8,640
8	2017	86,091	65,183	9,727	7,773	1,230	5,670	294,615	510,364	40,075	27,125
9	2018	88,674	67,139	10,408	8,006	1,267	5,840	294,615	546,089	70,142	45,214
10	2019	91,334	69,153	11,136	8,246	1,305	6,015	294,615	584,316	102,512	62,933
11	2020	94,074	71,228	11,916	8,494	1,344	6,195		625,218	431,967	252,562
12	2021	96,896	73,364	12,750	8,748	1,384	6,381		668,983	469,458	261,412
13	2022	99,803	75,565	13,643	9,011	1,426	6,573		715,,812	509,791	270,353
14	2023	102,797	77,832	14,598	9,281	1,469	6,770		765,919	553,172	279,389
15	2024	105,881	80,167	15,619	9,560	1,513	6,973		819,533	599,820	288,524
16	2025	109,058	82,572	16,713	9,846	1,558	7,182		876,900	649,971	297,759
17	2026	112,329	85,049	17,883	10,142	1,605	7,398		938,283	703,878	307,099
18	2027	115,699	87,601	19,135	10,446	1,653	7,620		1,003,963	761,810	316,548
19	2028	119,170	90,229	20,474	10,759	1,702	7,848		1,074,241	824,057	326,108
20	2029	122,745	92,936	21,907	11,082	1,754	8,084		1,149,438	890,930	335,782
NPV											648,166

Table 7
Optimum values of exergy efficiency and NPV for different combination of parameters.

Case	Parameters	Value of the parameter		ε_{total} (%)	NPV (€)
1	$P16$, $T15$	$P16 = 8.013$ bar $T15 = 453.15$ K		24.38	681,546
2	$P16$, X_{14,O_2}	$P16 = 8.013$ bar $X_{14,O_2} = 2.5\%$		24.24	723,360
3	$P16$, $n_{sc,air}$	$P16 = 8.013$ bar $n_{sc,air}$[a] $= 75\%$	 $n_{sc,air}$[b] $= 85\%$	24.08	667,876
4	$T15$, X_{14,O_2}	$T15 = 453.15$ K $X_{14,O_2} = 2.5\%$		24.44	710,633
5	$T15$, $P11$	$T15 = 453.15$ K $P11$[a] $= 1.313$ bar $n_{sc,biogas} = 75\%$	 $P11$[b] $= 1.093$ bar	24.30	666,548
6	$P16$, X_{14,O_2}, $P11$	$P16 = 8.013$ bar $X_{14,O_2} = 2.5\%$ $P11$[a] $= 1.313$ bar	 $P11$[b] $= 1.093$ bar	24.24	728,131
7	$P16$, X_{14,O_2}, $P11$, $n_{sc,air}$	$P16 = 8.013$ bar $X_{14,O_2} = 2.5\%$ $P11$[a] $= 1.313$ bar $n_{sc,air}$[a] $= 75\%$	 $P11$[b] $= 1.093$ bar $n_{sc,air}$[b] $= 85\%$	24.25	728,131
8	$P16$, X_{14,O_2}, $P11$, $T15$, $n_{sc,air}$, $n_{sc,biogas}$	$P16 = 8.013$ bar $X_{14,O_2} = 2.5\%$ $P11$[a] $= 1.313$ bar $T15 = 453.15$ K $n_{sc,air}$[a] $= 75\%$ $n_{sc,biogas} = 75\%$	 $P11$[b] $= 1.093$ bar $n_{sc,air}$[b] $= 85\%$	24.54	765,746

[a] The value maximizes ε_{total}.
[b] The value maximizes NPV.

analysis. The optimum values of exergy efficiency and the NPV for different combination of parameters are given in Table 7.

5.5. Scenarios

Three scenarios are considered so as to see the change of the exergy efficiency and of the NPV.

The first scenario considers the reduction of the condensate losses returning from the plant to 5% instead of 30% relative to the steam delivered to the plant. This would incur an additional installation cost of 20,000 €

The second scenario considers the installation of an economizer at the end of the steam boiler to preheat the water incoming water. The economizer could reduce the temperature at which the gases are thrown to the environment at 383,15 K. This would also incur an additional purchase and installation cost of 20,000 €.

The third scenario refers to the combination of the two scenarios above, which would incur a cost of 20,000 €.

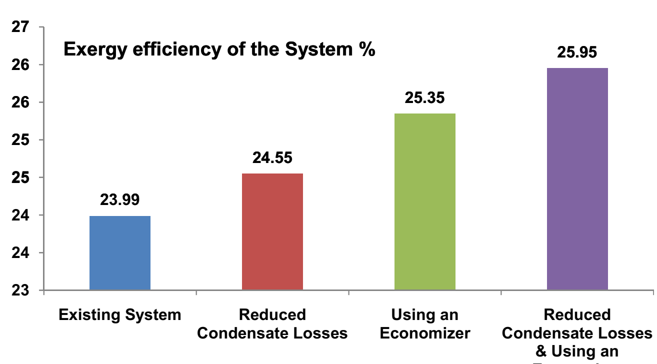

Fig. 4. Exergy efficiency of the existing system and of the three scenarios.

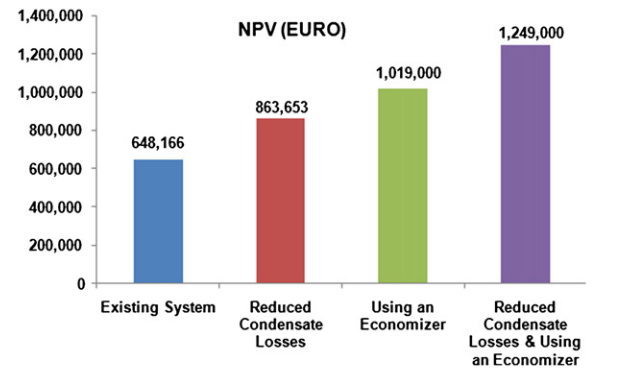

Fig. 5. Net Present Value of the existing system and of the three scenarios.

The values of the exergy efficiency and the NPV for the existing system and for the three scenarios are given in Figs. 4 and 5 respectively.

6. Conclusions

Based on the exergetic and the economic analysis given above, it can be concluded that the anaerobic treatment of high strength waste such as whey is a sustainable investment, at least for a substantial volume of whey.

The exergetic efficiency of the system is rather low. This is mostly because of the high exergy losses at the steam cycle. Improvements at specific equipment, such as the burner, the boiler and the heat exchangers, based on a better system design, could improve the overall efficiency.

Nonetheless, the calculation of the Net Present Value of the investment reveals that it is a sustainable way for the company to treat the whey it produces. The Net Present Value is calculated on the basis that the whole capital cost of the investment will be covered completely by a bank loan received by the company. It should also be noted that the calculation of the NPV does not take into account any possible governmental funding given for such investments which could be as high as 40% of the TCI. Also, it is not taken into account any savings resulting from the costs incurred by the alternative ways of treating whey.

Based on the results of the sensitivity analysis and the optimization, it can be said that the change of the system parameters can influence the exergy efficiency of the system as well as the NPV. Specifically, the exergy efficiency can be improved by almost 2.3%, while the NPV can be improved by over 18%.

The three scenarios examined in Section 5.5 showed that the improvement of exergy efficiency and NPV can be much greater when some the condensate losses in the plant are minimized and an economizer is installed at the end of the steam boiler. Specifically:

- The minimization of the condensate losses would improve the exergy efficiency by 2.33% and the NPV by 33.25%.
- The installation of an economizer at the end of the steam boiler would increase the exergy efficiency by 5.67% and the NPV by 57.2%.
- The combination of these two modifications to the system would rise the exergy efficiency by 8.17% and the NPV by 92.7%.

Appendix A

The equations given below are taken from “Thermal Design and Optimization” [16].

Thermodynamic Properties of Whey (untreated, recirculated and treated):

- The specific enthalpy of whey is given by:

$$\overline{h} = x_{H2O} \cdot \overline{h}_{H2O} + x_s \cdot \overline{h}_s \quad (A.1)$$

The enthalpy of water for any temperature and pressure is given by equation:

$$\overline{h}_{H2O}(T,P) = \overline{h}_{f,H2O}(T) + \overline{v}_{f,H2O} \cdot [P - P_{sat}(T)] \quad (A.2)$$

The enthalpy of the solute $\overline{h}_s$ is taken for the reference state ($T_0 = 298.15$ K and $P_0 = 1.013$ bar) and is assumed to be constant for the range of temperature and pressure of this system.

- The specific entropy of whey is given by:

$$\overline{s} = x_{H2O} \cdot \overline{s}_{H2O} + x_s \cdot \overline{s}_s \quad (A.3)$$

The enthalpy of water for any temperature and pressure is given by equation:

$$\overline{s}_{H2O}(T,P) = \overline{s}_{f,H2O}(T) \quad (A.4)$$

The entropy of the solute $\overline{s}_s$ is also taken for the reference state ($T_0 = 298.15$ K and $P_0 = 1.013$ bar) and is assumed to be constant for the range of temperature and pressure of this system.

Thermodynamic properties of Biogas and Air:

Biogas and air are both assumed to be mixtures of ideal gases. So, the thermodynamic properties of both mixtures are taken by the following equations.

- The partial pressure P_k for each of the components of the mixture is:

$$P_k = \frac{n_k}{n} \cdot P \quad (A.5)$$

- The enthalpy of the mixture is given by:

$$H = \sum_{k=1}^{N} n_k \cdot \overline{h}_k \quad (A.6)$$

Since each of the components is treated as ideal gas, its enthalpy is a function only of the temperature, which is the same as the temperature of the mixture.

- The entropy of the mixture is given by:

$$S = \sum_{k=1}^{N} n_k \cdot \overline{s}_k \quad (A.7)$$

The entropy of an ideal gas is a function of its temperature and pressure. The temperature of the component is the same again with the mixture temperature but its pressure corresponds to the partial pressure of the component.

Physical, Chemical and Total Exergy equations:

- Physical exergy:

$$E^{PH} = \dot{m} \cdot [(\overline{h} - \overline{h}_0) + P_0 \cdot (\overline{s} - \overline{s}_0)] \quad (A.8)$$

- Chemical exergy:

$$E^{CH} = \dot{m} \cdot \left(\sum x_k \cdot \overline{e}_k^{CH} + R \cdot T_0 \cdot \sum x_k \cdot \ln(x_k) \right) \quad (A.9)$$

- Total Exergy:

$$E = E^{PH} + E^{CH} \quad (A.10)$$

Mass flow calculation

$$\dot{m} = \dot{Q} \cdot d \quad (A.11)$$

Pressure Loss calculation

- Reynolds Number:

$$\mathrm{Re} = \frac{u \cdot D}{\nu} \quad (A.12)$$

- Friction factor calculation (Colebrook Equation):

$$\frac{1}{\sqrt{f}} = -2 \cdot \log\left(\frac{k_s/D}{3.7} + \frac{2.51}{\mathrm{Re} \cdot \sqrt{f}} \right) \quad (A.13)$$

- Pressure loss:

$$\frac{\Delta P}{\rho} = f \cdot \left(\frac{2 \cdot L}{D} \right) \cdot \left(\frac{4 \cdot Q}{\pi \cdot D^2} \right)^2 \quad (A.14)$$

Exergy Destruction

For steady state, and taking no heat losses into account, the exergy balance is written:

$$0 = -\dot{W}_{CV} + \sum_{inlet} \dot{m}_{inlet} \cdot \overline{e}_{inlet} - \sum_{outlet} \dot{m}_{outlet} \cdot \overline{e}_{outlet} - \dot{E}_D \quad (A.15)$$

Exergy Efficiency

$$\varepsilon = \frac{\dot{E}_{\mathrm{Product}}}{\dot{E}_{Fuel}} \quad (A.16)$$

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