ENERGY AND EXERGY ANALYSIS OF COMBINED HEAT AND POWER SYSTEMS – WASTEWATER TREATMENT IN DAIRY INDUSTRIES FOR ENERGY PRODUCTION

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THESIS

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ΕΝΕΡΓΕΙΑΚΗ & ΕΞΕΡΓΕΙΑΚΗ ΑΝΑΛΥΣΗ ΣΥΣΤΗΜΑΤΩΝ ΣΥΝΔΥΑΣΜΕΝΗΣ ΠΑΡΑΓΩΓΗΣ ΘΕΡΜΟΤΗΤΑΣ ΚΑΙ ΙΣΧΥΟΣ, ΕΠΕΞΕΡΓΑΣΙΑ ΑΠΟΒΛΗΤΩΝ ΓΑΛΑΚΤΟΒΙΟΜΗΧΑΝΙΩΝ ΓΙΑ ΠΑΡΑΓΩΓΗ ΕΝΕΡΓΕΙΑΣ

Περίληψη

Τις τελευταίες δεκαετίες, υπάρχει έντονο ενδιαφέρον στις εναλλακτικές μορφές ενέργειας, ως αποτέλεσμα των αυξημένων ενεργειακών απαιτήσεων σε συνδυασμό και με το πρόβλημα της κλιματικής αλλαγής. Επιπρόσθετα, η συνεχής αύξηση του πληθυσμού και η εκβιομηχάνιση των κοινωνιών οδηγούν συχνά στην υποβάθμιση των οικοσυστημάτων, στα οποία στηρίζεται η ανθρώπινη ζωή. Για το λόγο αυτό, στη σύγχρονη βιομηχανική κοινωνία είναι αδήριτη η ανάγκη για την κατάλληλη επεξεργασία των διαφόρων αποβλήτων που προέρχονται από τις βιομηχανίες πριν την απόρριψή τους, προκειμένου να προληφθεί η ρύπανση του εδάφους και των υδάτινων συστημάτων (λιμνών, ποταμών, θάλασσας, υπόγειων υδροφόρων). Το τυρόγαλο που προέρχεται από τις βιομηχανίες γάλακτος κατά την διαδικασία παραγωγής τυριού είναι ένας από τους σημαντικότερους βιομηχανικούς ρυπαντές που από τη φύση του περιέχει υψηλό οργανικό φορτίο (COD). Συγχρόνως όμως, το τυρόγαλο αποτελεί την πρώτη ύλη για παραγωγή βιοαερίου.

Η παραγωγή βιοαερίου και άλλων εμπορεύσιμων προϊόντων με ταυτόχρονη μείωση του COD μέσω κατάλληλων μεθόδων, αποδεικνύουν ότι το τυρόγαλο είναι μια σημαντική πηγή ενέργειας και όχι ένας απλός ρυπαντής. Η παρουσία βιοαποικοδομήσιμων συστατικών στο τυρόγαλο σε συνδυασμό και με τα πλεονεκτήματα της διεργασίας της Αναερόβιας Χώνευσης συγκριτικά με άλλες μεθόδους, καθιστούν την μέθοδο αυτή ως ιδιαίτερα κατάλληλη για την επεξεργασία των αποβλήτων αυτών.

Στην παρούσα διατριβή μελετάται η τεχνολογία της αναερόβιας χώνευσης για την επεξεργασία των αποβλήτων τυρόγαλου σε συνδυασμό με την χρήση μικροστροβίλων για την παραγωγή ενέργειας. Η επιλογή της χρήσης μικροστροβίλων έναντι άλλων συστημάτων οφείλεται στα πλεονεκτήματα τους που τους καθιστούν ικανούς να χρησιμοποιηθούν σε εφαρμογές κατανεμημένης παραγωγής ηλεκτρικής ενέργειας, «smart grids», υβριδικά συστήματα και συστήματα συμπαραγωγής.

Αρχικά παρουσιάζεται μία ανασκόπηση των πιο αντιπροσωπευτικών εφαρμογών αναερόβιας χώνευσης για επεξεργασία αποβλήτων τυρόγαλου τόσο σε πιλοτική όσο και σε εργαστηριακή κλίμακα. Επιπρόσθετα, γίνεται μία προσπάθεια αναγωγής των αποτελεσμάτων των διαφόρων ερευνών σε μια κοινή συγκριτική βάση, προκειμένου να αποτυπωθεί η κατάσταση της τεχνολογίας σε αντίστοιχα γραφήματα.

Στη συνέχεια, αναπτύσσεται ένα μοντέλο προσομοίωσης του συστήματος αναερόβιας χώνευσης σε συνδυασμό με έναν μικροστρόβιλο και εξετάζονται δύο διαφορετικά σενάρια. Στο πρώτο σενάριο μελετάται η ενσωμάτωση ενός εμπορικά διαθέσιμου μικροστροβίλου στο σύστημα αναερόβιας χώνευσης για παραγωγή ηλεκτρικής ενέργειας, με καύση μόνο ενός μέρους του παραγόμενου βιοαερίου στον μικροστρόβιλο, ενώ το υπόλοιπο καίγεται στον καυστήρα για παραγωγή ατμού. Στην περίπτωση αυτή, η επιλογή του καταλληλότερου μικροστροβίλου έγινε με σκοπό να επιτευχθεί η μέγιστη παραγωγή ηλεκτρικής ενέργειας με ταυτόχρονη κάλυψη των θερμικών απαιτήσεων (παραγωγή ατμού) της μονάδας.

Στο δεύτερο σενάριο μελετάται η περίπτωση μέγιστης παραγωγής ηλεκτρικής ενέργειας μέσω μικροστροβίλου, χωρίς κανένα περιορισμό όσον αφορά την παραγωγή σε ατμό. Τα δεδομένα για την μοντελοποίηση του συστήματος αναερόβια χώνευσης προέρχονται από ένα εργοστάσιο παραγωγής τυριών που λειτουργεί στην Ελλάδα, ενώ τα δεδομένα για τους μικροστροβίλους έχουν ληφθεί από τους αντίστοιχους κατασκευαστές τους. Ως εκ τούτου, προέκυψαν δύο διαφορετικά συστήματα τα οποία αναλύονται και εκτιμώνται σε σχέση με τα διαθέσιμα στοιχεία στη βιβλιογραφία.

Στη συνέχεια διεξάγεται εξεργειακή ανάλυση των συστημάτων αυτών. Τα αποτελέσματα έδειξαν ότι τα συστήματα αυτά μπορεί να επιτύχουν υψηλούς βαθμούς απόδοσης, παρά την εμφάνιση υψηλών τιμών καταστροφών εξέργειας και αναστρεψιμοτήτων, κυρίως στον καυστήρα για το πρώτο σενάριο και στον θάλαμο καύσης του μικροστροβίλου για το δεύτερο σενάριο. Στη συνέχεια, πραγματοποιήθηκε οικονομική ανάλυση μέσω της μεθόδους Καθαρής Παρούσας Αξίας (ΚΠΑ). Τα αποτελέσματα δείχνουν πως πρόκειται για κερδοφόρες επενδύσεις, με υψηλά κέρδη από τον πρώτο χρόνο λειτουργίας.

Επιπλέον, διεξήχθη παραμετρική ανάλυση ως μέθοδος βελτιστοποίησης. Στην περίπτωση αυτή, εξετάσθηκε η επίδραση ορισμένων σημαντικών παραμέτρων λειτουργίας όπως ο ισεντροπικός βαθμός απόδοσης του στροβίλου και του συμπιεστή και η επίδραση διαφόρων θερμοκρασιών κυρίως στη συνολική εξεργειακή απόδοση των συστημάτων και στη τιμή της ΚΠΑ. Τα αποτελέσματα έδειξαν ότι τα συστήματα αυτά μπορούν να επιτύχουν υψηλές αποδόσεις και τιμές ΚΠΑ με κατάλληλη επιλογή των παραμέτρων σχεδίασης.

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Abstract

Today, there is a growing interest in alternative forms of energy as a result of increased demands for energy in combination with the concerns on global warming due to the use of fossil fuels Furthermore, the successive increase of population and the industrialization of societies have resulted in the degradation of various ecosystems on which human life relies. For this reason in the modern industrial society, the proper pretreatment of industrial effluents before their discharge is especially important, in order to prevent the pollution of the ground and the water resources (e.g. lakes, rivers).

Cheese whey coming from dairy industry is one of the most important industrial pollutants, which carry a high organic load in terms of Chemical Oxygen Demands (COD). However, the potential production of biogas or other marketable products with the simultaneous high COD reduction through appropriate treatment proves that cheese whey has to be considered as an energy resource rather than a pollutant. The presence of biodegradable components in the cheese whey coupled with the advantages of anaerobic digestion process over other treatment methods, makes anaerobic digestion an attractive and suitable option.

The present thesis examines the technology of anaerobic digestion for cheese whey wastewater treatment coupling with micro turbines for energy production. The decision for the use micro turbines is due to their many advantages regarding the conventional reciprocating engines, which make them suitable for distributed generation applications, smart grids, hybrid and cogeneration systems.

Firstly, this thesis presents a review regarding the most representative applications of anaerobic treatment of cheese whey being exploited or being under research. Moreover, an effort has been made to classify the common characteristics of various research efforts and find a comparative basis, as far as their results are concerned.

A simulation model of Anaerobic Digestion System coupled with a micro turbine has been developed and two different scenarios are examined. The data for the Anaerobic Digestion system modeling has been obtained from a dairy industry operating in Greece and the data for the micro turbines are obtained from the corresponding manufacturers.

The first scenario examines the incorporation of a commercially available gas micro turbine to the anaerobic digestion system for electricity production from the burning of a part of the biogas produced in the micro turbine. The remaining amount of biogas is forwarded to a burner for steam production. Thus, in this case the selection of the appropriate micro turbine is based on achieving the maximum electricity generation, while the plant requirements in steam are covered.

The second scenario investigates the case for the maximum electricity production without any limitation in the steam production and the most suitable micro turbine is chosen. Thus two different systems are obtained, analyzed and validated with available data in the literature.

An exergetic analysis of the above mentioned scenarios follows. The results showed that these systems can achieve high efficiencies, despite of the high exergy destructions and irreversibilities appearing mainly in the burner for the first scenario and in the micro turbine's combustion chamber for the second scenario. Then, an economic analysis through the method of Net Present Value is conducted. The results reveal that these investments are profitable, with high savings and incomes from the first year of their operation.

Furthermore, a parametric analysis is carried out as a method for the systems optimization. The influence of important performance parameters such as turbine and compressor isentropic efficiencies and some temperatures variations, mainly to the total exergy efficiency and the Net Present Value are investigated. The results showed that these systems can achieve high efficiencies and NPV with a proper choice of the design parameters.

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Finally, I would like to dedicate this PhD thesis to the most important man in my life my son Achilles.

Aspasia Chatzipaschali

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Nomenclature

T	Temperature
P	Pressure
$\bar{h}$	Specific enthalpy
H	Enthalpy
$\bar{s}$	Specific entropy
S	Entropy
$\bar{e}$	Specific exergy
$\bar{v}$	Specific volume
D	Pipe diameter
$\dot{E}$	Exergy
d	days
x	Mass rate
$\dot{m}$	Mass flow
M	Molecular weight
$\dot{Q}$	Volume flow
LHV	Low Heating Value

NPV	Net Present Value
NCF	Net Cash Flow
TCI	Total Cost of Investment
k_s	Roughness of pipe
PR	Pressure ratio
Re	Reynolds number
F	Friction factor
i	Discount rate or rate return
u	Mean fluid velocity
n	Moles
ν	Kinematic viscosity
$\dot{W}$	Power
R	Air gas constant
L	Length equivalent
K	Borrowed funds
ε	Borrowing rate
t	Year, 1..20
v	Number of years for loan repayment
ns	Isentropic efficiency
AD	Amortization installment

Abbreviations

AD Anaerobic Digestion.

BOD Biological (Biochemical) Oxygen Demand.

BOD_5 Five day Biological (Biochemical) Oxygen Demand.

COD Chemical Oxygen Demand.

CHP Cogeneration Heat & Power

TOC Total Organic Carbon

CR COD Removal (%).

CW Cheese Whey.

HRT Hydraulic Retention Time (day).

IC Influent COD (g COD/L).

OLR Organic Load Rate (g COD/(L day)).

T Temperature (°C).

Reactor's Abbreviations

AAFEB Anaerobic Attached Film Expanded Bed.

ABR Anaerobic Bio film Reactor.

AF Anaerobic Filter.

AHR Anaerobic Hybrid Reactor.

AMMBR Anaerobic Moving Biofilm Reactor.

AnRBC Anaerobic Rotating Biological Contact Reactor.

AP	Anaerobic Pond.
ARBCR	Anaerobic Rotating Biological Contact Reactor.
ASBBR	Anaerobic Sequencing Batch Biofilm Reactor.
ASBR	Anaerobic Sequencing Batch Reactor.
CSTR	Continuously Stirred Tank Reactor.
DFFR	Downflow Fixed Film Reactor.
DSFFR	Downflow Stationary Fixed Film Reactor.
DUHR	Downflow-Upflow Hybrid Reactor.
ECSB	External Circulation Sludge Bed
EPFAUF	Ecological Pretreatment Followed by Anaerobic Upflow Filter.
FBR	Fluidized Bed Reactor.
FFR	Fixed Film Reactor.
HAR	Hybrid Anaerobic Reactor.
HBR	Hybrid Bed Reactor.
MAB	Multichamber Anaerobic Bioreactor.
NMABR	Novel Moving Anaerobic Biofilm Reactor.
NMR	Novel Multiplate Reactor.
RBCR	Rotating Biological Contact Reactor.
SDFA	Semi-continuous Digester and chemical Flocculant Addition.
SMFBR	Sub-Merged Fixed Bio film Reactor.
SWD	Solid Waste Digester
TSMAMD	Two Stage Mixed Anaerobic Membrane Digester.

UAF Upflow Anaerobic Filter.

UAFFR Upflow Anaerobic Fixed Film Reactor.

UAPBR Upflow Anaerobic Packed Bed Reactor.

UAR Unmixed Anaerobic Reactor.

UASB Upflow Anaerobic Sludge Blanket.

UASFF Upflow Anaerobic Sludge Fixed Film Reactor.

UFFR Upflow Fixed Film Reactor.

UFFLR Upflow Fixed Film Loop Reactor.

UHR Upflow Hybrid Reactor

Chapter 1 Introduction

This chapter refers to the motivations for undertaking this thesis. A brief introduction is first carried out about the trends in energy market, followed by a discussion on the role of the main systems (anaerobic digestion process, micro turbines) studied in this thesis.

1.1 Background & Motivation

During the last decades the rapid growth of the economic level and of industrial activity of most countries has caused an increase in energy demand in the form of fossil fuels with direct impact on the environments, such as global warming. One of the most promising renewable energy sources for energy generation is biomass in the form of biofuels such as biogas. Numerous studies focusing on various aspects of this energy source appeared in the literature during the past three to four decades. Biogas can be produced by industrial wastewaters, municipal solid waste, energy crops, animal wastes and various other materials decomposition [1]. Its main constituents are carbon dioxide and methane and it can be utilized for various purposes. It can be used for heat or steam production, for electricity production with CHP, as an industrial energy source and as vehicle fuel (in its upgraded form). Furthermore, after upgrading it can added into the natural gas distribution system and can be used as fuel in fuel cells [2].

In the developed and developing countries, industrial wastewaters are becoming increasingly useful in biogas production. Among others the liquid effluents produced by dairy industries and cheese producers, such as whey produced during cheese and cream cheese making process, represents one of the most important industrial pollutants, which carry a high organic load in terms of COD [3, 4].

Because of this high organic load of whey, Anaerobic Digestion (AD) constitutes an appropriate treatment method [5] not only to remove a great amount of COD but also to produce biogas, which can then be used to cover a significant part of the energy needs of the industry. It is estimated that one liter of cheese whey can produce forty five liters of biogas containing 55% methane, while, simultaneously, the COD is expected to be reduced by 80%. Thus, for each liter of cheese whey twenty liters of methane (CH_4) can be produced, which are equivalent to 740kJ (700 Btu) of energy production [6].

It is clear from the above brief discussion that cheese whey can be an important source for electrical energy production after its AD treatment. Several systems have been suggested in the literature that can be used for this reason. Among them, the micro turbines have a leading role in the energy market. Their advantages make them an ideal solution for numerous applications.

The micro turbines are miniatures of larger gas turbines and they are suitable for distributed generation applications, because of their advantages such as high specific power, multi-fuel operation, low maintenance costs, ability to provide reliable and stable power, parallel connection to serve larger loads and low pollutant emissions [7].

In this work, several applications of micro turbines in connection to cheese whey AD treatment are considered and evaluated.

1.2 Thesis aims and objectives

The incorporation of commercially available micro turbines in anaerobic digestion treatment plant which is based on real operating data is not a simple process. The limitations and the requirements of the anaerobic digestion treatment plant have to be satisfied along with the specifications and the requirements of the micro turbine, in order to obtain a simulation system model, which can be applied on an industrial scale. For an optimum incorporation, a careful selection of key operating parameters should be done and a suitable control strategy should be applied.

This thesis aims at analyzing a cogeneration system for electricity and heat production through anaerobic digestion treatment of cheese whey wastewater. The main goal is to better understand the processes that take place in these systems and give recommendations for improving its performance. The main objectives of this research are:

- Gain knowledge on the technology of cheese whey wastewater anaerobic digestion treatment.
- Review the available anaerobic digestion treatment methods which have been used on pilot and laboratory scale for cheese whey treatment,
- Development of a detailed and accurate computational model for cheese whey wastewater anaerobic digestion treatment which will be based on realistic data.
- Estimate the steam production for covering the thermal needs of the plant.

- Study the incorporation of micro turbine in anaerobic digestion treatment plant system for cheese whey wastewater in order to obtain the maximum possible energy production depending on the requirements in each case for the two scenarios examined.
- Assessing the economics of the biogas cogeneration plant from cheese whey anaerobic digestion treatment and comparing it with the use of natural gas as fuel.
- Performing exergy analysis of a simulation model that has been developed in order to find the locations and magnitudes of the exergy destructions and exergy losses.
- Techno-economic optimization of a cogeneration system for electricity and heat production through anaerobic digestion of the cheese whey wastewaters. To our knowledge, there is any known in the literature to suggest a method to optimize the performance over the whole plant.

1.3 Thesis contribution

It is believed that the work carried out in this thesis contributes towards the optimized utilization of cheese whey wastewater as a resource for biogas production and cogeneration of electricity and heat. More specifically:

- In order to evaluate the state of technology concerning the COD removal rate ability and the biogas production from cheese whey anaerobic digestion treatment through different types of reactors and systems in use, an effort has been made, to establish a common comparative basis [8-10].

- Modeling of a cheese whey anaerobic digestion treatment plant was developed in EES simulation environment with realistic data from an industrial system in operation [10-12].
- The incorporation of commercially available micro turbines in the cheese whey anaerobic digestion treatment plant has been studied through exergetic and economic analysis [11, 12].
- The economic assessment of biogas production and utilization in the dairy industry itself is examined [11, 12].
- The techno economic optimization through a parametric analysis is described [11, 12].

In the literature there are studies on whey AD systems focusing mainly on the parameters which affect the process of AD, the COD removal and the biogas production rate (for more details see [9]). However, the number of studies on the utilization of biogas systems to produce energy (heat and electricity) from whey wastewaters is limited [13, 14] in comparison to other waste types [15-21]. Moreover, a special case of an anaerobic digestion system coupled with a gas micro turbine is examined both by exergetic, economic and parametric analysis.

Finally, it is noted that the methods and model developed in this thesis can be extended to other industrial process problems.

A list of papers published in international journals and conferences are enlisted here:

1. Chatzipaschali A. Aspasia, Stamatis G. Anastassios (2012): ‘’Biotechnological Utilization with a Focus on Anaerobic Treatment of Cheese Whey, Current Status and Prospects’’. Journal: Energies (5), p.3492-3525.
2. Chatzipaschali A. Aspasia, Stamatis G. Anastassios (2014): Exergetic and economic analysis of a cheese whey wastewater anaerobic treatment plant with a cogeneration system. Journal: Desalination and Water Treatment, 56 (5), p.1223-1230.
3. Chatzipaschali A. Aspasia, Stamatis G. Anastassios, Nikolaos Andritsos (2016): Incorporating available micro gas turbine in an anaerobic digestion system: Matching considerations and performance evaluation. Submitted for publication.
4. Chatzipaschali A. Aspasia, Stamatis G. Anastassios (2012): ‘’Anaerobic Digestion of cheese whey with focus on COD removal rate’’, International Conference on New Energy, Biological Engineering and Food Security, Published in Lecture Notes in Information Technology (LNIT) ISSN: 2070-1918, Hong-Kong, September 4-5, 2012.
5. Chatzipaschali A. Aspasia, Stamatis G. Anastassios (2012): ‘’Removal of polluting load and energy production from cheese whey anaerobic digestion’’, 1st Environmental Conference of Thessaly, Skiathos, September 8-10, 2012.
6. Chatzipaschali A. Aspasia, Stamatis G. Anastassios (2013): Exergetic and economic analysis of a cheese whey wastewater anaerobic treatment plant with a cogeneration

system. 4th International Conference on Environmental Management, Engineering, Planning and Economics, Mykonos Island, June 24 to 28.

1.4 Thesis outline

This thesis is organized in nine chapters. Following this introduction, the literature review of the cheese whey anaerobic digestion treatment is given in Chapter 2. The main characteristics of the cheese whey wastewaters and the various methods for its managing and utilization as a resource for the production of added value products production are discussed. A comparison follows among the most representative anaerobic digestion systems used on a laboratory or pilot scale for biogas production and cheese whey pollutant load reduction. Chapter 3 gives the technology background of micro turbines. Chapter 4 presents the model development of the anaerobic digestion system for cheese whey treatment coupled with a micro turbine for cogeneration production of heat and electricity. In Chapter 5 two scenarios of the system developed are studied. In the first scenario, the objective is to select the most suitable micro turbines among five commercially available. In the second scenario the case of the highest possibly electric power production is investigated and the most suitable micro turbine is chosen. In Chapter 6 the systems obtained from both scenarios examined are analyzed and an exergetic analysis is performed. Chapter 7 presents the economic analysis of both of these two systems through NPV method. In Chapter 8 a methodology to improve the performance of these systems obtained for the whole operating range is carried out through parametric analysis. Finally, Chapter 9 concludes this research and makes recommendations for future work.

Chapter 2 Literature review

In this chapter the general characteristics of the effluents of cheese whey and a brief description is given of different methods for managing and utilization of cheese whey as a source for producing added value products. Then, a detailed presentation follows of the most representative anaerobic digestion systems used in a laboratory or pilot scale for biogas production and for the reduction of cheese whey pollutant load. An effort has been made to identify common characteristics of these systems and establish a comparative basis, as far as their results are concerned. The related technology status is expressed by corresponding diagrams of COD removal rate versus Hydraulic Retention Time and Organic Load Rate. Finally, some existing applications of industrial scale anaerobic digestion systems are described.

2.1 Introduction on cheese whey

Effluents that come from cheese factories can be divided into two basic categories. The first category includes the washing and pasteurization waters, mixed with detergents and remnants of milk in the piping machinery. The cheese whey belongs in the second category. The effluents of the first category have low organic load and are usually treated on site in aerobic treatment units. Although the cheese whey volume is about 1/3 of the total effluents, it contains a high organic load (high values of COD and BOD) making it extremely polluting to be allowed for direct disposal on land or in water systems [22-27].

Treatment of wastewaters coming from cheese factories and mainly cheese whey, is based on physicochemical and/or biological methods. However, the reagent cost in physicochemical methods is very high and the removal of soluble COD is poor. Consequently, biological processes are often preferred [28], with anaerobic digestion (AD) to be the most suitable for such high organic loading effluents [29]. The major advantages of this process compared to other treatment methods are: low cost, high energy efficiency and process simplicity [5]. Furthermore, this method can achieve an adequate removal of BOD and COD from cheese whey and the methane production is close to the theoretical yield [6].

There are several reviews in the literature [30-40] focusing on the cheese whey as a resource to produce added value products (lactose, proteins, ethanol, biogas etc.) and presenting the different production methods. Some other reviews focus on the anaerobic digestion of dairy industry effluents including cheese whey [22, 41-44], on the two phase anaerobic treatment of various wastewaters [45-47] and on the anaerobic digestion of various industry effluents [48, 49]. The above reviews constitute a useful starting point for this section of the Thesis which aims to update the research and technology status. These research and technology status concern the use of cheese whey with focus on anaerobic digestion systems removing the organic load content (COD) of cheese whey and producing biogas. More specifically, this section presents the general characteristics of the effluents of cheese whey and gives a brief description of different methods for managing and utilization of cheese whey as a source for producing added value products. Then, it presents in detail the most representative anaerobic digestion systems used on a laboratory or pilot scale for biogas (methane) production and cheese whey pollutant load reduction. An effort has been made (for the first time to our knowledge) to reduce common characteristics of these systems and establish a comparative basis, as far as their results are concerned. The related technology status is expressed by constructing diagrams of COD removal rate versus Hydraulic Retention Time (HRT) and Organic Load Rate (OLR). Finally, some existing applications of industrial scale anaerobic digestion systems are described.

2.2 Composition of cheese whey

Cheese whey is a liquid byproduct of the cheese making process that contains most of the water soluble components and water present in milk [50-52]. More specifically, after casein curd separates from the milk, following coagulation of the casein proteins through the action of chymosin or mineral/organic acid, the remaining watery and thin liquid is called whey [35, 53]. It has a yellow/green color or sometimes even a bluish tinge, depending on the quality and type of milk used. The composition of cheese whey depends also on the quality and the composition of evaluated milk and other parameters such as the techniques of cheese production, the amount of yeast, the acid used for coagulation, the period and the temperature of coagulation [54]. Cheese whey can come from any kind of milk. In western societies the cows' milk is the most popular while in other regions of the world, goat's, sheep's and even camel's milk can be used in dairy industries [35].

This byproduct represents 85-95% of the milk volume and retains 55% of the milk nutrients [23]. The most abundant of these nutrients are lactose (45-50 g/L), soluble proteins (6-8 g/L), lipids (4-5 g/L) and mineral salts (8-10% of the dry extract). The mineral salts are mainly NaC1 and KC1 (more than 50%), calcium salts (mainly phosphate) and others. Also, cheese whey contains appreciable quantities of lactic and citric acid, non-protein nitrogen compounds (like urea and uric acid) and B group vitamins [24, 33, 55, 56].

According to the production process and the coagulation of casein, the cheese whey is divided into two categories, the acidic whey, which has a pH less than 5 ($pH<5$) and the sweet whey with pH between 6 and 7 ($6<pH<7$) [57]. The acidic cheese whey usually contains fewer proteins and due to its acidic flavor and high salt content it is used with limitations for alimentation [31, 33, 55]. The main differences between these two types of cheese whey are the content of mineral elements, the acidity and the composition of the fraction of whey proteins. Table 2-1 presents the typical composition of sweet and acid whey.

Table 2-1 Typical composition of sweet and acid whey [56, 58].

Components	**Sweet whey (g/l)**	**Acid whey (g/l)**
Total solids	63-70	63-70
Lactose	46-52	44-46
Proteins	6-10	6-8
Calcium	0.4-0.6	1.2-1.6
Phosphate	1-3	2-4.5
Lactate	2	6.4
Chloride	1.1	1.1

The whey which is produced from cheese coagulated with rennet is low in acidity, while the one coming from the production of fresh acidic cheeses like ricotta and cottage cheese is medium acid or acid cheese whey [56].

Cheese whey is characterized as an organic pollutant with high BOD and COD in the range of 40.000 – 60.000 and 50.000 – 80.000 ppm, respectively [3, 4]. Lactose is largely responsible for the high BOD and COD, as more than 90% of whey BOD_5 is due to it (lactose) [4, 59]. Furthermore, 97.7% of the total COD was accounted for by lactose as well as by lactate, proteins and fats [4, 55, 60, 61]. On the other hand, protein recovery reduces the COD of the whey only by about 10.000 ppm [33, 62] or 12% [23]. The organic load of cheese whey, as given from various literature sources, is shown in Table 2-2.

In addition to the above components, some heavy metals in low quantities are also encountered in the cheese whey, as it is indicated in several works. In a tank with a mixture of raw whey and industrial washing water the following elements elements were identified: Cd, Cr, Cu, Hg, Pb and Zn [63]. Moreover, in a recent work [64], small quantities of Al, Cd and Pb were observed in cheese whey powder. The presence of heavy metals in cheese whey enhances its high polluting load because of the serious toxic effects in the organisms caused by heavy metals.

Table 2-2 Organic load of Cheese Whey

Components	Value	References
BOD_5	40.000-60.000 ppm	[4]
	30.000-50.000 ppm	[33],[65]
	>30.000 ppm	[35]
COD	50.000-80.000 ppm	[4], [66]
	60.000-80.000 ppm	[33]
	60.000-100.000 ppm	[65]
	>60.000 ppm	[35]

It has been estimated that the world whey production is over than 160 million tons per year [35, 62, 67]. Approximately half of the total world cheese whey production is discarded directly to the environment, representing a significant loss of resources and a major pollution problem. Its disposal affects the physical and chemical soil structure, with result the decrease in the crop yield, while the release into water resources reduces aquatic life, by depleting the dissolved oxygen [33, 56]. Recent research in Greece (Vouraikos River) has shown that the water pollution and the ecological risk to aquatic life are very high, since the concentration of the disposal untreated cheese whey in the aquatic ecosystem is five times more than the permitted limits [68]. The high pollutant load of cheese whey along with its continuously growing production (>2% every year, [69]), lead to a serious management problem. Nine kilogram of cheese whey are produced from making 1 kilogram of cheese [33].

2.3 Cheese whey management

According to Siso [33], only 50% of the total produced quantity of cheese whey is treated and converted into various food products. This percentage is going to increase as a result of continued research efforts in the field of whey utilization coupled with the pressure on casein and cheese producers by relevant legislation concerning the disposal of liquid effluents [62]. At the same time, new products and technologies are developed for the treatment of cheese whey wastewaters. In European Union it has been mentioned that 45% of cheese whey that is treated and converted into different food products is used directly in liquid form, 30% in powder form, 15% as lactose and non-lactose byproducts and the rest as cheese whey protein concentrates [70, 71].

According to Mawson [31], the different ways of disposal or use of cheese whey could be divided into three main categories: *Direct use or disposal*, where the cheese whey is used with very little or no further processing. This category includes the traditional use of cheese whey as an animal feed and the direct use of the whole or deproteinated cheese whey as a component of food or drinks. *Direct stabilization*, where the cheese whey is treated with physical or chemical ways in order to become more stable for microbial degradation. The techniques used include: protein recovery with ultrafiltration or heat denaturizing, concentration by reverse osmosis and/or with evaporation, crystallization or drying of lactose. *Conversion processes*, where the lactose is converted into other compounds through the activity of microorganisms (biotransformation) or through chemical reactions.

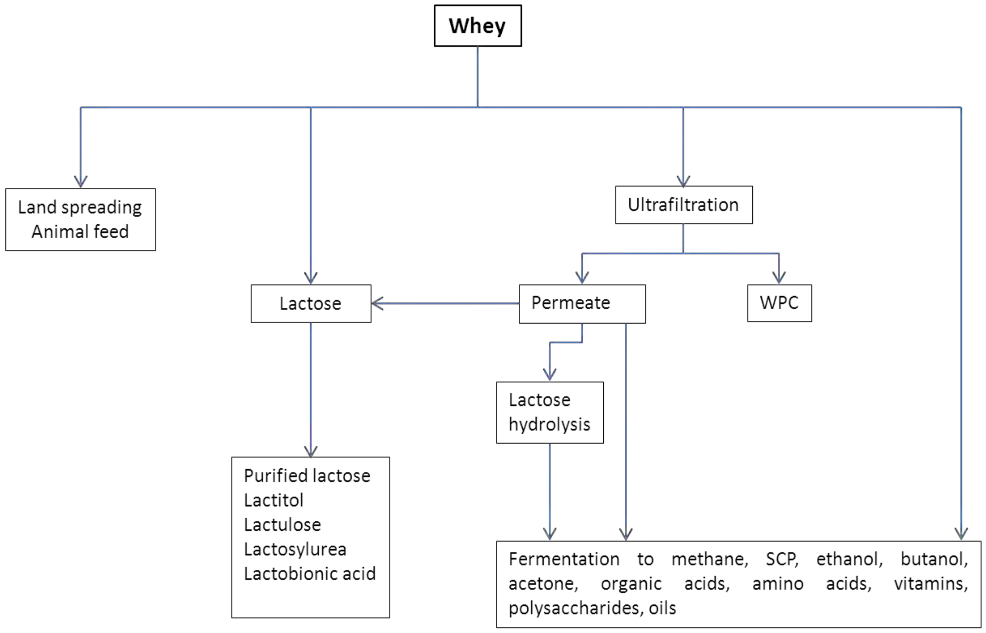
The direct supply of liquid cheese whey into drinking water for animals is limited, because of the high quantity of lactose and mineral proportions. Its use as agricultural fertilizer has a disadvantage, because of the high amount of salt that leaves behind. Besides, the transport of liquid cheese whey is very expensive [33] and therefore a large proportion of the produced cheese whey is dried in order to produce powder cheese whey [70, 72, 73]. In this form, the quality of fresh cheese whey can be kept fresh for a longer period of time and also its handling and transportation are easier. The powder cheese whey is used mainly in animal feeding and in smaller quantities can be used in human foods, like ice cream, bread, sweets, sauces, dairy products etc [33, 62].

The initial phase in most processes of cheese whey utilization consists of the recovery of the fraction of proteins. The cheese whey proteins, which represent 15 – 22% of milk proteins, are considered beneficial for health and are characterized by high nutritional value and therapeutic potential [35, 62, 74, 75]. The major whey proteins are: a-lactalbumin, b-lactoglobulin, bovine serum albumin (BSA), bovine 1g G. However, there are also minor whey proteins such as lactoperoxidase, lacto (trans) ferrin and other minor compounds. Riechel *et al.* [76] using the capillary electrophoresis method detected bovine lactoferrin that exists in very small concentration in cheese whey. Through separation of the cheese whey proteins from whey by ultrafiltration, diafiltration or processing of membranes, whey protein concentrates –WPC, which are used in food industries [33, 35, 72, 77] or Whey Protein Isolate – WPI are produced. The WPC contains 30-90% proteins while the WPI contains more than 90% proteins in the dry matter [36]. The WPC is free of salts, so it is suitable for all kinds of human food, even for dietetic or baby food [70]. Other non-food uses of whey proteins deal with specific properties of single proteins used in cosmetology and pharmacology [36]. The physical and functioning properties of whey proteins are solubility, viscosity, cohesion and adhesion, emulsifying properties, water sorption and gel-forming properties [78]. The different uses of whey proteins are based on these properties (for more details see [36]).

During the milk processing for WPC production, the produced permeate (big quantities of streams reach in lactose) continues to be a pollutant containing lactose more than 70% of milk whey. Lactose, as stated earlier, contains a noteworthy pollutant load. Therefore, the disposal of permeate creates problems quiet similar to the disposal of raw cheese whey [77]. The solubility and the sweetness of lactose is low compared to other sugars, like those of glycose, galactose, fructose and sucrose [79, 80]. Most of the products of lactose are recovered from the whey or of whey permeate through the crystallization process (for details see [73, 79, 81]).

Lactose is used mainly as a component of food, infant formulae and filler or coating agent for tablets in the pharmaceutical industry. However, it has rather limited application in food products because of its low digestibility and poor solubility (ability to crystallize) [36]. Lactose is used also as substrate in the synthesis of derivatives such as lactulose, lactitol, lactobionic acid, lactosyl urea, galocto-oligosaccharides and hydrolysed lactose syrup [36, 73, 79, 80].

Hydrolyzed lactose solutions possess greater sweetening power than lactose and are used in confectionary and ice creams industries replacing saccharose or starch syrop [33, 80]. Technology for the production of hydrolysed lactose syrup is well developed and is used, for instance, to produce suitable dairy products for lactose-intolerant individuals [79]. Chemical hydrolysis is possible in low pH (<1.5) and high temperature (more than 150 ^{o}C), but the enzymatic hydrolysis using Aspergillus and Kluyveromyces enzymes is usually the method of choice [62, 73, 79, 80]. Lactose in whey or permeate may be used as substrate for the elaboration of valuable compounds by fermentation. The well-known examples are the production of ethanol [62], single cell protein (SCP) production in yeast-based bioprocesses and the biogas (methane) and hydrogen production. Other bioproducts are: organic acids (acetic, propionic, lactic, citric, gluconic, itaconic and gibberellic), amino acids (glutamic, lysine and threonine), vitamins (B12 and B2 or cobalamins and riboflavin respectively), polysaccharides (xanthan gum, dextran, phosphomannan, pullulan and gellan), oils (lipids), enzymes (b-galactosidase and polygalactorunase) and other compounds (fructose-diphosphate, 2, 3-butanediol, calcium, magnesium acetate, ammonium, lactate butanol and glycerol [33, 36, 73, 80, 82]. Figure 1 shows the products that come from the processing of whey lactose.



(SCP: Single cell protein and WPC: whey protein concentrates).

Figure 2-1 Applications of CW – lactose [36].

In a recent experimental research project conducted by Antonopoulou *et al.* [83], it was proved that the diluted cheese whey can be an energy source for production of electrical energy using a two-chamber mediator-less microbial fuel cell (MFC; H-type), replacing the substrate of lactose and glucose. The maximum power density obtained using diluted cheese whey (normalized to the geometric area of the anodic electrode), was 18.4 mW/m^2, that is equivalent to current density 80 mA/m^2 and voltage of MFC 0.23V. The coulombic efficiency was only 1.9%, which could be attributed to biochemical oxidation of the organic substratum by the indigenous non-electrogenic microbial consortium contained in the raw wastewater. Optimization and further development by the improvement of MFC design and with pretreatment of the cheese whey (sterilization or pasteurization) might increase both density and coulombic efficiency making the procedure economically viable [84]. Finally, the economic and environmental importance of cheese whey utilization for the production of bio hydrogen has recently been identified and there is a growing research interest focusing on this subject [55, 84-90].

2.4 Use of Anaerobic Digestion systems – production of biogas and removal COD

In case where cheese production plants have growing disposal problems and cannot afford high investment costs for whey valorization technologies (such as whey protein and lactose recovery, spray drying, etc.), the biological treatment is an imperative process to reduce the pollutant load. Because of the high organic content of cheese whey, anaerobic digestion constitutes an excellent treatment method [5]. This fact has also been proved by Spachos and Stamatis [13], through exergy and economic analysis of a modeled cheese whey treatment anaerobic digestion system.

The anaerobic digestion process includes degradation and stability of organic matters by microorganisms under anaerobic conditions and leads to the biogas (a mixture of carbon dioxide and methane) and biomass formation [48, 66, 91]. In particular, with regard to cheese whey, this complex process consists of three sequential steps: hydrolysis of lactose (and proteins), fermentation and methanogenesis [36, 92] as presented in Figure 2-1. Anaerobic digestion involves several mixed bacteria species. According to Audic *et al* [36], about 90% of hydrolyzed organic matter is converted into biogas in the methanogenesis process. It is estimated that 1 liter of cheese whey can produce 45 liters of biogas containing 55% methane and the expected COD removal is 80%. For each liter of cheese whey 20 liters of CH_4 can be produced, which are equivalent to 700 Btu of energy production [6]. However, despite the energy potential and waste reduction, the use of anaerobic digestion is not widespread in the dairy industries, mainly due to the slow reaction rates (high HRT) and the relative process instability in conventional reactors [24].

Malaspina *et al.* [93] asserted that cheese whey is quite a difficult substrate to treat anaerobically (especially in highly loaded reactors) because of its high organic contain, low bicarbonate alkalinity (50 meq/L), tendency to acidify rapidly, granulation difficulties and its tendency to produce an excess of viscous exopolymeric materials of probable bacterial origin that reduce significantly the sludge settling ability and could be reason for washout of the biomass. However, the development of some technologies and systems of anaerobic digestion (which will follow) for the cheese whey treatment, prove that it is a worthy and valuable source of energy. Table 2-3 presents different biogas production systems using cheese whey which have been studied on a laboratory or pilot scale while Figure 2-2 illustrates the maximum COD removal (%) versus HRT for these systems.

Table 2-3 Cheese whey treatment systems.

Waste	Reactor	IC	pH	Biogas/ CH_4 yield	HRT	OLR	T	CR	Ref.
CW	DFF	66		0,28 m^3CH_4/kg COD_{rem}	4.9	13		75	[94]
CW	DFF	66		0,34 m^3CH_4/kg COD_{rem}	6.6	8.3		76	[94]
CW	AF				4		30-21-12.5	92-85-78	[95, 96]
CW	UASB	28.7	7.18	9.57 lCH_4/l feed/day	5	5.96	33	98	[97]
Sour(acidic)whey	UFFLR	79	6.7	5.6 m^3/m^3day	5	14	35	95	[98]
CW high strength	UASB	77			11.6	28.5	35	95	[99]

CW	UASB	28.8	7.15		5	5.96	33	98	[100]
CW	UAR*	72.2	4.5		20	3.5	35	36	[101]
Deproteinated CW	DSFFR	13			5	2.6	35	88	[102]
Strength lactic casein whey permeate	FBR	7	4.3	0.396 m^3CH_4/kg $COD_{rem.}$	0.4	7.7	35	90	[103]
Sweet whey powder	AAFEB	5	7		0.65	10	35	92	[6]
Cheddar CW	AnRBC*	64			5	10.2	35	96	[104]
CW	SDFA	69.8			4.3	16.1		99	[105]
CW	(SBR)***	3.9	7		3	1.04	20	97	[106]
Whey in a dried form	AHR (R1)	1	7- 8	0.69 (CH_4yield)	0.75	1.3	20	80	[107]
Whey in a dried form	AHR (R2)	10	7- 8	0.55 (CH_4yield)	0.75	13.3	20	90	[107]
Cheese was/ter	UASB	2.05	6.7	0.32lCH_4/gCODelim.	0.07	31	35	90	[108]
CW	AHR	10		0.354 (CH_4yield)	1.7	6.11	35	97	[109]
(Salty) CW	RBCR	30	7	4.1l/$l_{digester}$/day	3	10	37	85	[110]
(Salty) CW	(MB)			3.2l/$l_{digester}$/day	2		37	83	[111]
CW	UF (SFR & MFR)	9	4-7		0.33	35		87	[112]
CW	HBR	22			2	11		95	[113]
CW	EPFAUF)*	20	7		5	4	34-36	98	[24]
CW	ASBR				0.33		28-32	90	[114]
Raw CW	TSMAMD*	68.6	7.9 - 8.5	>0.70(CH_4yield)	4	19.78	37	98.5	[4]
CW	UASB*	58.4	7 -8	0.77 (CH_4yield)	2.46	24.6		97	[5]
CW	DUHR	68			7	10		97	[93]
CW	UAFFR	70		0.72 (CH_4yield)	2	35	37	81	[115]
CW, butter, fresh milk	AHR*	5.34	5.22	0.28-0.35 (CH_4yield)	1.9	2.82	35	97	[116]
CW & diluted poultry manure	CSTR	91		2.2L/$L_{reactor}$/day	18	4.9	35	77	[65]
Whey mix & cow manure	AD [1]				14		35	74	[117]
CW	UASB*	10.82			0.75	15	34-36	99	[118]
CW&dairy manure	CSTR	29			10		34	54	[54]
CW	FBR	0.8-10			0.1-0.4	6 - 40	35	63-87	[119]
Deprotainated CW	UASB	11			1.5	7.1	35	94	[120]
CW	AP **	4.4			8	0.55		96	[121]
CW	CSTR & UAF*			0.55m^3/kg $COD_{rem.}$	4			95	[122]
CW	2 CSTRs*	10			10	0.97	55	96.4	[123]
CW	UASFF	57		3.75l/day	2	25	36	97.5	[66]
Diluted CW	UASB	37	7.2		6	6.2	35	98	[29]
CW	NMR	42.5			2.83	15	34	92	[124]
CW	AF	8.1			4.3	1.9	22-25	97	[125]
CW	NMABR	10.2			1	11.3	35	89	[126]
CW	NMABR	10.2	7 - 8		0.6	15.3	35	81	[126]

CW	UAPBR	59.4	6.5				0.66	59.28	25		94.5	[127]

[Two phase anaerobic treatment, **Anaerobic-Aerobic process, ***Sequential anaerobic and aerobic step in a single digester, [1]Anaerobic digester (batch, fed batch, batch)].*

From Figure 2-2 it becomes clear that is quite difficult to assess the effectiveness of the used systems, at least with respect to the superiority of any particular technology. Various types of reactors have been utilized, from simple to more complex types such as UASB (for more details see [41]).

In general, it is difficult to compare systems operated in different laboratories, not only because of the possible differences in the anaerobic sludge characteristics [24], but also because of the differences in operating parameters (such as temperature, pH, OLR, total solids and volatile fatty acids content, toxicity, HRT, inoculums type) and the composition of the anaerobic digestion effluent.

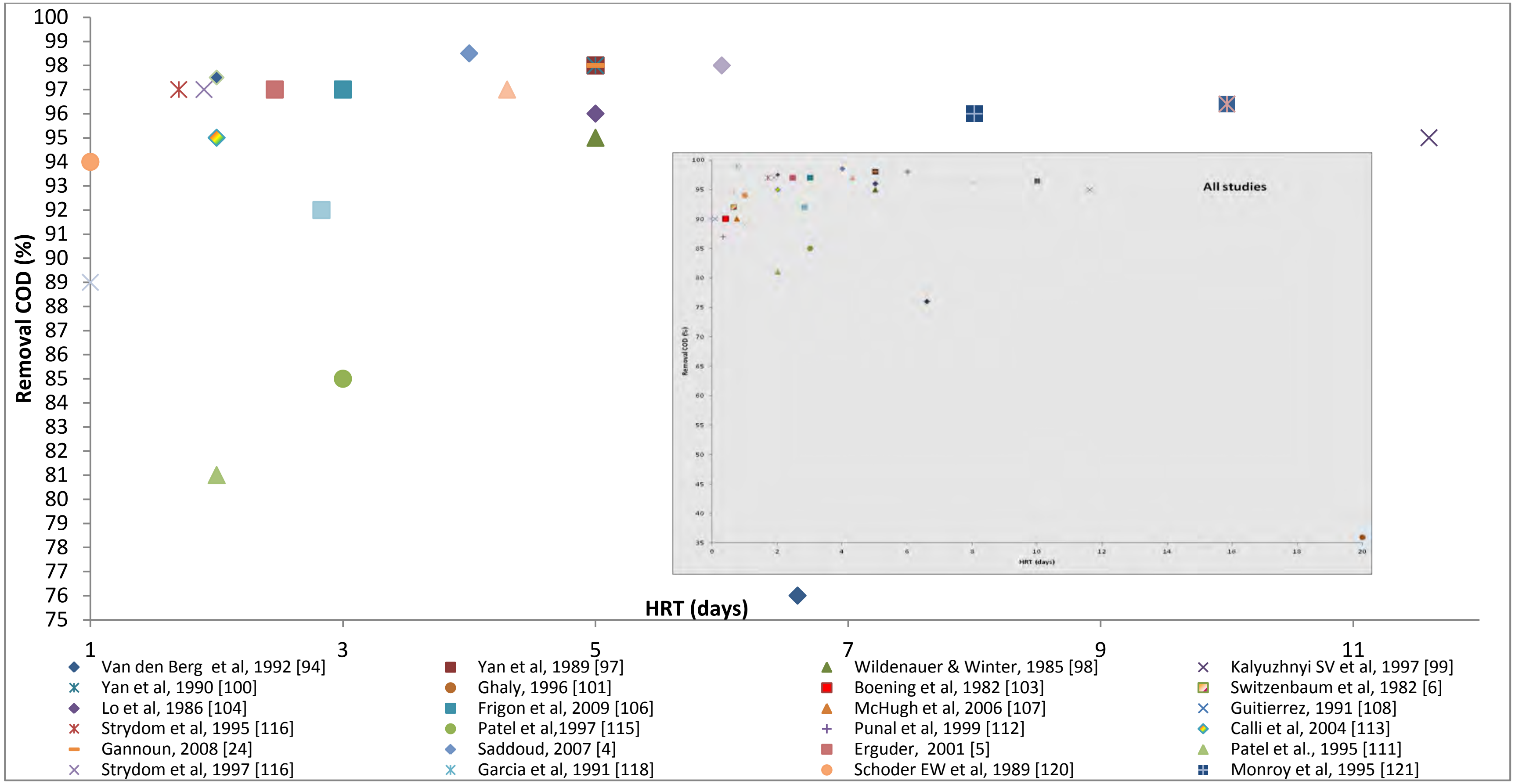


Figure 2-2 Maximum COD removal (%) versus log HRT for various CW treatment systems.

Since anaerobic digestion is a biochemical process driven by consortia of various microorganisms which are involved in the transformation of complex high-molecular-weight organic compounds to methane, any stress or disturbance on the system may lead to a change in species types and their relative population levels, which is ultimately reflected in the reactor performance. Therefore, the organic material added as inoculums in the fermentative organic substrate is one of the most important factors affecting anaerobic digestion of organic waste. High microbial loading inoculums material needs to be added in the mixture of biomass when start-up the anaerobic digester. The inoculums have significant effects on biogas productions (for more details see[128]). The selection of the appropriate inoculum is very important and depends on the composition of the substrate (C/N/P, alkalinity). For example, Gannoun *et al*. [24], reported that for anaerobic digestion of ecological pretreatment cheese whey with optimum composition for the anaerobic digestion system the inoculum was obtained from an active biogas digester of fruit and vegetable waste treatment [129].

The composition of the effluent of the anaerobic digestion is also important for either direct discharge or the following anaerobic digestion. However, only a few works on cheese whey anaerobic digestion treatment can be found in literature [98, 114, 130], giving the detailed composition of the effluent of the anaerobic digestion. Most of the works reported only indicative data for the effluent (such as COD, VFA concentration, etc). Table 2-4 summarized some of the reported works on cheese whey anaerobic digestion treatment along with the inoculum type used and the anaerobic digestion effluent composition characteristics.

Table 2-4 Inoculums and effluents concentration of CW AD treatment

Waste	Reactor	Inoculum	Effluent	References
CW	UASB	Seed sludge from AnRBC used for treatment a mixture of CW and manure	COD: 457 mg/L, pH: 7.18, VFA: 18 mg/L	[97]
Sour (acidic) whey	UFFLR	Sewage sludge	COD: 3.9 g/L	[98]
CW (high strength)	UASB	Dispersed sludge from anaerobic lagoon treating meet industry wastewater	VFA< 0.5 gCOD/L	[99]
CW	UASB	Seed sludge from AnRBC used for treatment a mixture of CW and manure	COD: 457 mg/L, pH= 7.18, VFA: 18 mg/L	[100]
CW	UAR*	Seed material from unmixed An. Digester operating on dairy manure	COD: 33.02 g/L, Volatile solids concentrations: 17.9 g/L	[101]
CW	(SBR)***	Biomass for the inoculum came from a full scale anaer. digester treating fruit processing wastewaters	COD: 51±56 mg/L after aerobic step	[106]
Whey in a dried form	AHR (R1)	Anaerobic granular sludge originating from an internal circulation reactor treating wastewater from a commercial lactose alcohol	sCOD: 150-300 mg/L	[107]
Whey in a dried form	AHR (R2)	Anaerobic granular sludge originating from an internal circulation reactor treating wastewater from a commercial lactose alcohol	propionate: 500 mg/L, acetate: 100 mg/L	[107]
Cheese production wastewater	UASB	Cleaning water from cheese factory (cheese production wastewaters)	acetic & propionic acid concentration: 0.01-0.02 mg/L, COD: 65 mg/L	[108]
CW	UF (SFR & MFR)	Seed sludge from UAF mesophilic reactor treating wastewaters from tuna processing factory	SFR COD: 5 g/L & MFR COD:2 g/L	[112]
Pretreated CW	(EPFAUF)*	Inoculum from an active biogas digester of fruit and vegetable waste treatment		[24]
CW	ASBR	Inoculum from UASB treating poultry slaughterhouse wastewater		[114]
Raw CW	TSMAMD*	Inoculum From full scale AD treatment plant		[4]
CW	UASB*		COD: 1.428-1.975 mgCOD/Ll	[5]
CW	UAFFR	Inoculum from operating whey reactor	VFA: 0.94 g/Ll, COD: 16.4 g/L	[115]
CW, butter, fresh milk	AHR*	Inoculum from sewage sludge, rumen fluid and effluent from two other mesophilic lab-scale reactor		[116]
CW	UASB*	Sludge from anaerobic reactor treating whey in a single step		[118]
CW	2 CSTRs*	Inoculum from municipal wastewater treatment		[123]
CW	UASFF	Seed culture from wastewater treatment plant		[66]
Diluted CW	UASB	Inoculated with anaerobic mixed liquor from dairy wastewaters and glucose fed digesters	COD: 5g/Ll	[29]

[Two phase anaerobic treatment, ***Sequential anaerobic and aerobic step in a single digester]*

Depending upon different type designing criteria, anaerobic digestion can be categorized into several types such as: according to feeding mode (batch, semi-batch or continuous reactors), the temperature (psychrophilic, mesophilic and thermophilic reactors), the solid content (high or low solids reactors), the complexity [single stage or two (multi) stage reactors], the shape of the reactor (horizontal and vertical), the way microorganisms are retained in the reactor (fixed film, suspended growth and hybrid), moisture in the substrate (wet or dry digestion) [131-134]. In this work the anaerobic digestion categorization based on the number of anaerobic digestion phases (single/two phases AD system) is employed in order to present the time evolution of the reactors and to understand more clearly the reasons for two phase anaerobic digestion development. Therefore, it has been decided to divide the systems into groups, according to the type (of the design) of the used reactor and to compare the papers of each group in terms of the highest COD removal rate versus HRT and OLR.

2.4.1. Conventional (single phase) anaerobic treatment of cheese whey

In several dairy wastewaters treatment systems, AF are often used, being suitable for effluents with low concentration of suspended solids. Hakannson *et al.* [125], using AF were able to achieve a high organic removal efficiency (97% COD removal) with an influent concentration 8,100 mg/L but at low OLR of 1.9 kg COD/(m^3 day), at an operating temperature of 22-25 ^oC. Later, Viraraghavan *et al*. [95, 96] achieved COD removals between 78% and 92% for HRT 4 days, by using a laboratory scale plastic medium AF reactor. The temperature variation between 21–30 ^oC had no significant effect on the startup performance of the AF treating cheese whey, in terms of COD removal [135].

Some of the basic problems (clogging of the filters, dead zones, etc.) during the wastewater treatment with UAF come from the excessive accumulation of biomass, which limits the efficiency of the process. In order to overcome these problems, two laboratory scale single fed (SFR) and multi fed (MFR) UAF treating cheese whey wastewaters operated at OLR higher than 20 kg COD/(m^3 day) were studied and compared [112]. The feeding policy had an effect both on biomass concentration and activity. Specific activities of different trophic groups were higher in MFR. Therefore, the MFR system operation was efficient, especially at high organic loading rate and at the same time major problems inherent in this technology (filter clogging and dead zones), are avoided.

Other treatment systems use FFR. For instance, Van den Berg and Kennedy [94], used a pilot scale DFFR at an HRT of 4.9 days and at an OLR of 13 kg COD/(m^3 day) and achieved 75% COD removal and 0.28 m^3/kg $COD_{removed}$ methane yield. With increase of HRT to 6.6 days and reducing OLR to 8.3 kg COD/(m^3 day) the COD removal efficiency was slightly increased (1%) and the methane yield rose to 0.33 m^3/kg $COD_{removed}$.

Patel *et al.* [115], investigated AD of high strength cheese whey (70 g COD/L) using an UFFR and the maximum COD removal achieved was 81% at an HRT of 2 days and with charcoal support material. This type of reactor allows the effective digestion, both at low and high strength wastewaters (in terms of the organic materials and suspended solids) in a low HRT. The FFR was able to treat higher strength substrates (without nutrient additional and pH control) and had higher COD removal efficiency than FBR. However, a longer HRT (at least 5 days) is needed, in the FFR [136, 137].

Rodgers *et al.* [126], used a novel ABR with a vertically moving bio film system, called AMMBR. At an HRT of 1 day and OLR of 11.6 kg COD/(m^3 day), at mesophilic conditions (~35 ^oC), 89% COD removal efficiency was obtained. The decrease of HRT to 0.6 days and the increase of OLR to 15.2 kg COD/(m^3 day), led to the reduction of COD removal efficiency by 8%. The methane content in the produced biogas was 63% on average and the methane yield was 0.33 m^3/kg $COD_{removed}$, very close to theoretical value (0.35 m^3/kg $COD_{removed}$). This drop in COD removal with increase in OLR appeared also in [6], where a satisfactory COD removal efficiency (61-92%) achieved, using an AAFEB reactor at high organic load rate [8.2-22 kg COD/(m^3 day)] and under mesophilic conditions (~35 ^oC). However, increase of the influent strength from 5 to 20 kg COD/(m^3day) led to a drop in the COD removal efficiency from 83% to 58%. This reactor has also proved to be suitable for treatment at lower temperatures (28-31^oC) succeeding in satisfactory COD removal efficiency (77-93%).

A major problem during the cheese whey treatment is the usage of cheese whey to growth the yeast. Methods such as hydrolysis of the cheese whey, yeast adaptation and pressure selection are attempted to overcome this problem. A recent research [138], found that SMFBR is also a suitable method to face this problem and to treat cheese whey as well as all dairy effluents.

In order to clarify some of the above discussed aspects, the COD removal efficiency rate versus HRT (day) and OLR [g COD/(L day)] are presented in Figure 2-3. It is observed that Hakannson *et al*. [125], achieved the highest COD removal efficiency (97%) using AF for low strength cheese whey treatment, at the lowest OLR compared with the other studies. Wildenauer and Winter [98], using UFFLR with similar HRT but at much higher influent

COD and at higher OLR achieved slightly lower COD removal by 2%. It is also noteworthy that Boening and Larsen [103], using FBR and Switzenbaum and Daskin [6], using AAFEB achieved slightly lower COD removal (~5%), but at a much lower HRT (about ¼) compared to the other two studies [98, 125].

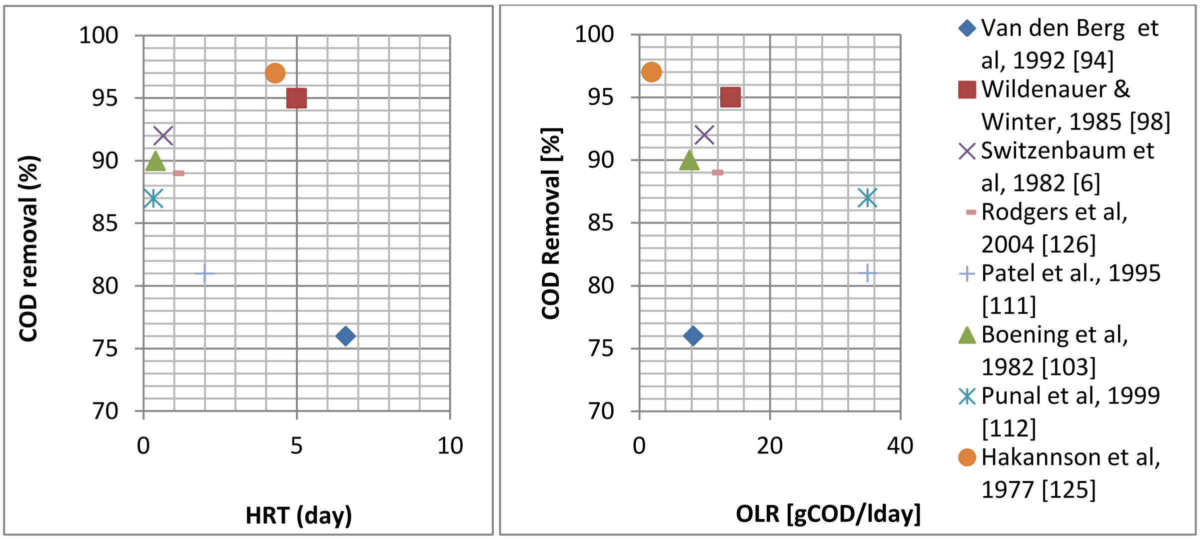


Figure 2- 3 Maximum COD removal versus HRT (day) and OLR [g COD/(L day)] using anaerobic filters, fluidized bed reactors and fixed film reactors for CW treatment.

The works mentioned up to this point, have been carried out with pH adjustment (pH control) in order to stabilize the operating conditions. The pH can be adjusted by adding bicarbonate [139, 140] and NaOH [123].

Another method of pH adjustment is the co-digestion of cheese whey with manure (poultry, cow, etc.). Co-digestion has been proved to be possible, without addition of any chemicals, with up to 50% participation of whey (by volume) in the daily feed mixture. With this method the specific biogas production remained roughly unchanged at the various whey fraction added in the feed mixture mainly because of the lower COD of cheese whey compared to that of manure [54, 65, 117]. The cheese whey anaerobic treatment is affected by the drop in pH. This effect can be handled with buffering action in a hybrid reactor, which is not possible in an UASB reactor without proper startup [42].

Due to the risk of strong acidification, the startup of the reactor is always a critical step [24]. The UASB reactor [141], can cope with preacidificated cheese whey wastewaters (pH of about 4) even at elevated OLR that eliminates the necessity of alkalinity supplementation by ensuring a proper startup. The COD removal efficiency reached up to 90% at an OLR 28.5 kg COD/(m^3 day) and 9.5 kg COD/(m^3 day) for mesophilic (~35 ^oC) and psychrophilic (20-30 ^oC) conditions respectively, under a stable operation regime [99]. Further exploitation of the reactor with the designed OLR of 6.5 g COD/(L day) showed sufficient operational stability with COD removal close to 95% on the basis of total COD.

COD removal close to 90%, at a high OLR of 31 kg COD/(m^3 day) and HRT of 1.7 h and methane production with an average value of 0.32 L CH_4/g $COD_{removed}$ obtained for cheese production wastewater (influent COD 2.05 g/L) using a laboratory scale UASB reactor under stable operating conditions [108]. Increase at OLR of about 30%, [higher than 45 kg COD/(m^3 day)] had as a result a reduction of the COD removal rate by 11-26%. This is a common problem in cheese whey treatment. As the substrate loading increases the acidogenic region extended into the methanogenic region in the upper part of the reactor until the whole region was acidogenic, leading to the failure of the reactor [100, 142].

Gavala *et al.*[29], using a laboratory scale UASB reactor (10 L useful volume) for cheese producing industry wastewaters (influent concentrations between 12 and 60 g COD/L), achieved a maximum COD removal efficiency of 98% at an HRT of 6 days with an influent

COD concentration of 37 g/L [OLR 6.2 g COD/(L day)]. The increase of influent COD concentration to 42 g/L (OLR to 7.5 g COD/(L day)) led to reduction of the COD removal efficiency (85%–90%). Further increase of HRT to 30-40 days and reduction of the OLR to 1.5-1.9 g COD/ (L day), led to decrease of COD removal to 81%. The maximum biogas production rate, during the conducted experiment was approximately 45 l/day with a methane content of 68%-74%.

Because of the instability caused by the strength of the influent in UASB reactor, the optimum influent substrate concentration for the proper system operation is determined to be between 25 and 30 g COD/1 at an HRT of 5 days [142]. In general UASB reactors are suitable for treatment of dairy wastewaters containing high concentrations of fat and grease with COD removal of about 90%, as has been reported by Cammarota *et al.* [143] and are the most common reactors for cheese whey treatment, since they can treat large volumes of wastewaters in a relatively short time [22]. However, the performance of the UASB system has not been yet discussed in detail. Systematic analysis of the reactor characteristics such as the operation stability, HRT, sludge granulation and the sludge discharging is still necessary. One of the most serious limitations of the UASB process is the relative long time that is required for the startup and for the granulation (even several months).

To overcome these limitations, a modification is required [5, 144]. A new model UASB reactor called one dimensional dispersed plug flow model was developed by the Kalyuzhnyi *et al*. [145]. This model focuses on the granular sludge dynamics along the height of the reactor, based on the balance between the dispersion, sedimentation and conversion with the use of one dimensional (with regard to the height of the reactor) equations.

Figure 2-4, presents the technology status based on the data of the works described so far, through COD removal rate versus HRT (day) and OLR (g COD/(L day)). It is observed that the highest COD removal was obtained both by Yan *et al*. [97, 100] for cheese whey treatment (influent COD concentration 28.8 g COD/L) and Gavala *et al.* [29] for diluted cheese whey treatment (influent COD concentration 37 g COD/L), proving the UASB reactors suitability to treat also high organic load raw wastewaters. In both studies there were no significant deviations regarding the influent COD concentrations as well as the OLR and the operating conditions (pH and temperature).

In addition to AF, FFR and UASB reactors, hybrid and ASB reactors are also used for dairy wastewater treatment. The UASFF reactor is a hybrid reactor which is a combination of an UASB reactor and an UFFR and it was developed in order to shorten the startup period. This reactor was used for the rapid biological conversion of organic matter of cheese whey to biogas. At HRT 48 h and temperature 36 °C, a COD removal rate of 97.5% in a sort startup time was observed. The highest biogas production rate of 3.75 L/d occurred at HRT of 36 h [66].

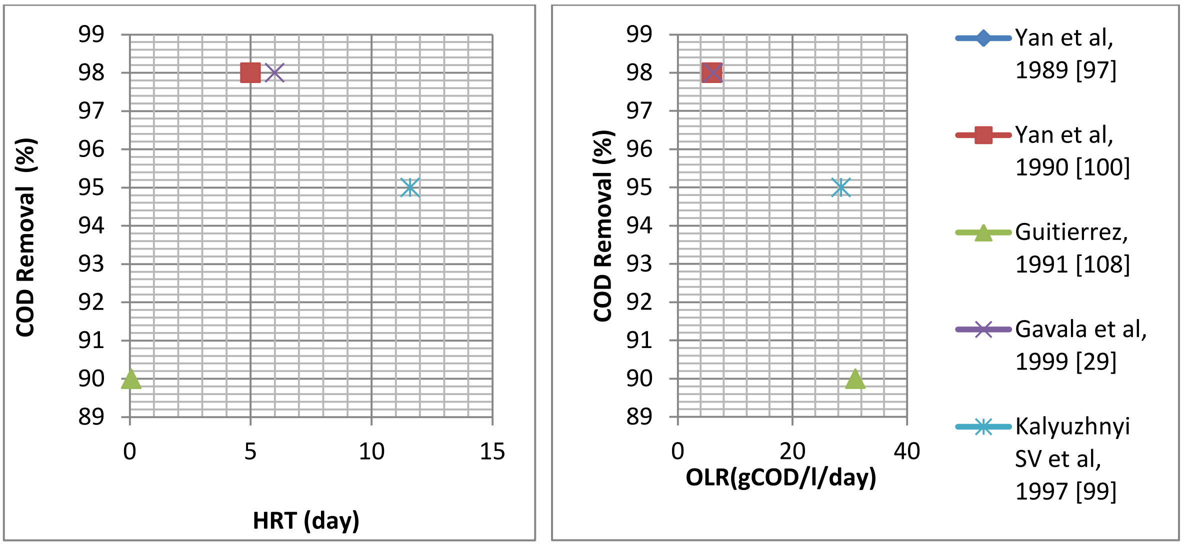


Figure 2-4 Maximum COD removal versus HRT (days) and OLR [g COD/(L day)] using UASB reactors for CW treatment .

The COD removal rate ranged from 90% to 97% at an OLR 0.82 to 6.11 kg COD/(m^3 day) and at an HRT 4.1 to 1.7 days has been obtained using mesophilic laboratory scale HAR (combining UASB and fixed bed design) [109], for cheese whey treatment with an influent substrate COD concentration of 10 g COD/L. The methane yield was 0.354 m^3 CH_4/kg $COD_{removed}$ at an HRT of 1.7 days. The anaerobic treatment of high strength acidic cheese whey using a laboratory scale UHR [113] resulted in a COD removal higher than 95%, at HRT of 2 days and at OLR of about 11 kg COD/(m^3 day). McHugh *et al* [107] used two laboratory scale reactors, R1 and R2, to treat low (1 kg COD/m^3) and high-strength (10 kg COD/m^3) whey wastewaters, respectively, under psychrophilic conditions (<20 °C) and obtained a high COD removal efficiency. The COD removal efficiencies of the R1 reactor varied in the range 70-80%, at OLR 0.5–1.3 kg COD/(m^3day), and temperature between 20 and 12 ^{o}C. The COD removal efficiency of the R2 reactor was higher than 90%, at OLR up to

13.3 kg COD/(m^3·day), between 20 and 14 °C. The decline in performance and granule disintegration was reversed by decreasing the OLR of R2 to 6.6 kg COD/(m^3 day). In the R2 reactor the biogas volumes generated throughout the study were about 20-25 L/day with biogas methane content between 55-65%, while in the R1 reactor the biogas methane content remained in the range 63-77%. Figure 2-5 depicts the COD removal rate achieved versus HRT and OLR for each reported study on hybrid reactors.

It should be mentioned that all the works on hybrid reactors for cheese whey treatment achieved high COD removal rates. However, a slightly better COD removal obtained by Najafpour *et al.* [66], at a short HRT of 2 days similar to that of Calli and Yukselen [113], but with almost double influent COD concentration and OLR, at 35 °C. High COD removal rate also achieved by McHugh *et al*. [107], by high organic load influent treatment, at 20 °C, proving that satisfactory COD removal can be achieved at low temperatures.

ASBR has also been studied for cheese whey treatment. The results have been promising, showing the real potential of this system as an alternative to continuous flow [139, 146]. Moreover, ASBR with mechanical stirring proved to be stable and efficient in removing organic matter at influent concentrations varied from 0.6 to 4.8 mg COD/(L day).

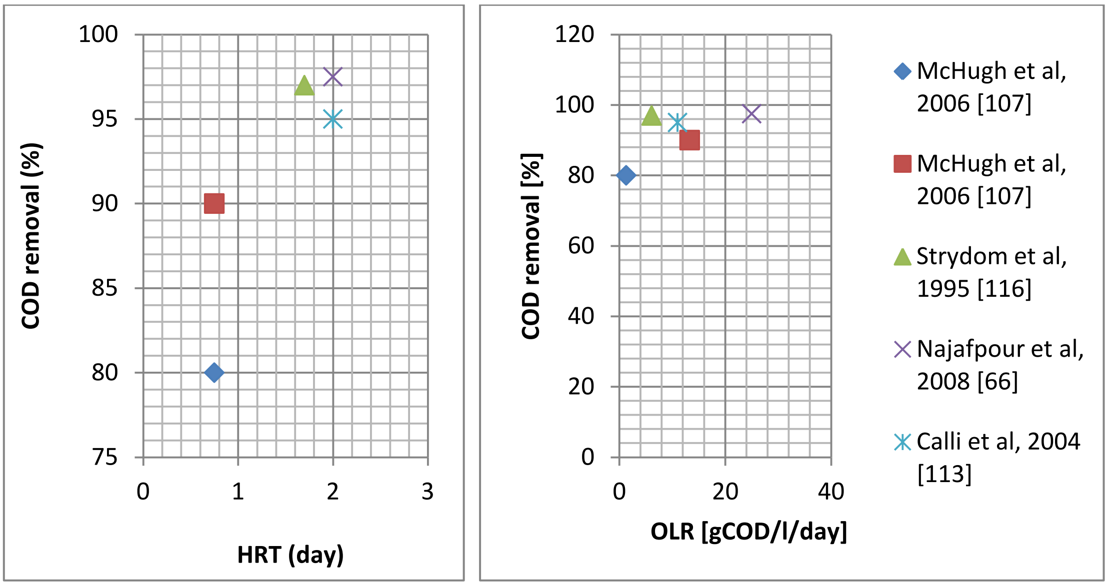


Figure 2-5 Maximum COD removal versus HRT (days) and OLR [g COD/(L day)] using hybrid reactors for CW treatment.

The COD removal rate for filtered samples was always up to 90%. The results were obtained with optimized alkalinity supplementation [114]. Damasceno *et al.* [147] assessed the behavior of a ASBBR containing immobilized on polyurethane foam for diluted cheese whey treatment when submitted to different OLR [2, 4, 8 and 12 g COD/(L day)] and feeding strategies (fill time of 10 min, 2 h and 4 h by a cycle time of 8 h). It was concluded that the concentration of total volatile acids varies with the time of filling. For the higher fill times, the highest concentrations were observed at the end of the cycle. Furthermore, no significant differences were detected in the maximum concentration of total volatile fatty acids for any of the conditions investigated.

Beyond the reactors mentioned up to this point, there are and some other alternative types of reactors. In a cheese factory in Canada, a novel multi plate reactor has been tried for cheese whey wastewaters. The influent COD ranged between 20 and 37 kg/m^3 and the OLR between 9 and 15 kg COD/(m^3·day). The maximum COD removal was quite high, 92%, and the average methane production rate was 4m^3/m^3 day. Activity level of the biomass maintained or increased during the research. The innovative design of the reactor seemed to be promising for cheese whey treatment and functioned effectively for one year [124].

Recently, the use of UAPBR to treat cheese whey proved to be a great strategy to achieve high COD removal efficiency in a short time. COD and lactose removals rose to 94.5% and 99%, repectively, at HRT of 16 h and room temperature (25 °C). The highest methane yield was achieved at 16 h of HRT and the highest volumetric rate of biogas production was achieved at HRT of 6 h [127].

ARBCR was used to treat anaerobically salty cheese whey. The optimum performance was achieved at an HRT of 3 days and at 37 °C and the resulting COD removal was 85%. The methane content in the biogas was close to 74% [110]. A similar COD reduction of 83% was achieved using a MAB for the anaerobic treatment of salty whey diluted with dairy effluents, at an HRT of 2 days and at 37 °C. The methane content in the produced biogas was 68% [111]. Figure 2-6, illustrates the COD removal rate, versus HRT (days) and OLR [g COD/(L day)], reported on certain alternative types of reactors.

It is clearly shown in Figure 2-6 that Najafpour *et al.* [127] achieved the highest COD removal rate at lower HRT and the highest OLR compared with the other two studies. It is also remarkable that this study was carried out at low temperature (25 °C), while the other works carried out at mesophilic conditions (34–37 °C).

In the conventional single reactor systems, as reported up to this point, there is a sensitive balance between the acid-forming and methane-forming microorganisms which are kept together, since both groups differ significantly in terms of physiology, nutritional needs, growth kinetics and parametric to environmental conditions. The problems of stability and control in conventional design applications have led the researchers to new solutions [45].

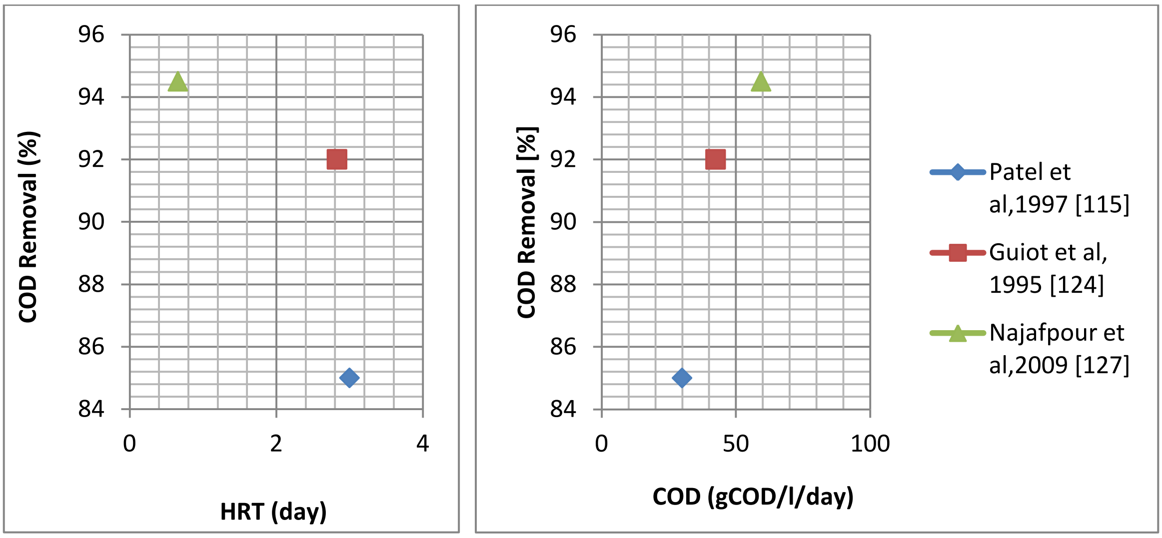


Figure 2-6 Maximum COD removal versus HRT (days) and OLR [g COD/(L day)] using alternative types of reactors for CW treatment.

2.4.2 Two phase (two stage) anaerobic treatment of cheese whey

The idea of developing the anaerobic digestion as a two-step procedure came from the fact that the process of the anaerobic digestion consists of two groups of different sets of activities [4]. Pohland and Ghosh [148] were the first to suggest the physical separation of the two groups of microorganisms, acid and methane formers, in two separate reactors. Optimum environmental conditions for each microorganisms group should be provided, in the reactors in order to enhance the overall process stability and control. The performance of acidogenic reactor (acid phase) is particularly crucial for the two phase anaerobic effluent stabilization, since the acidogenic reactor should provide suitable substrate for the subsequent methanogenic reactor (methane phase) [149]. Hall [150], summarized the advantages and disadvantages of one and two phase anaerobic treatment.

In order to investigate the two stage anaerobic digestion of cheese whey, various combinations of reactors have been used. UASB reactors were used as acidogenic and methanogenic reactors [151], or CSTR and UAF were used for acidogenesis and methanogenesis, respectively [122]. With the latter combination system, in the upflow methanogenic filter, 95% COD removal was attained at 35 ^{o}C and HRT 4 days, with biogas production rate of 0.55 m^3/kg $COD_{removed}$. Similar COD removal (93%) at an HRT of 5 days was achieved by another combination system using AnRBC reactors one for each stage [104]. Saddoud *et al*. [4] investigated a system consisting of a stirred acidogenic reactor followed by a methanogenic reactor coupled with a membrane filtration system for the removal of soluble effluents and the preservation of solids. The average removals of COD, BOD_5 and TSS were 98.5%, 99% and 100%, respectively, with daily biogas production higher than 10 times the reactor volume and biogas methane content higher than 70%. However, the flux declined because of the formation and compaction of a cake layer on the membrane surface caused by the particles inside the pores of the membrane.

Yang *et al.* [123] comparing one and two phase thermophilic anaerobic digestion systems for cheese whey treatment concluded that the two phase process was more suitable for the management of cheese whey wastewaters, with maximum COD removal rate and yield of methane production were 116%, 43% and 6% respectively, higher than those of the single phase system. This conclusion also follows from the evaluation of anaerobic digestion of three different dairy effluents (cheese, fresh milk and powder/butter) using a laboratory scale mesophilic two stage system. For effluents from the cheese factory at an OLR of 2.82 kg COD/(m^3 day), 97% of COD removal was achieved [116]. Cheese processing effluents were also used to determine the biokinetics of mesophilic acidogens. At pH 7 and temperature 36.2 °C, the maximum microbial growth (μ_{max}), the half saturation coefficient (K_s), the maximum microbial growth rate (Y) and the microbial decay rate (K_d) were calculated to be 9.9 $days^{-1}$, 134 mg COD/1, 0.29 mg MVSS/mg COD and 0.14 $days^{-1}$, respectively [22, 152].

Ghaly [101] used an UAR in order to investigate the effects of a two stage anaerobic digestion, with and without control of pH at the methanogenesis stage. The results indicated that by controlling the pH (by alkali addition) of the methanogenic stage, a significant increase in the biogas production rate and methane yield have been obtained, as well as a decrease in COD and solids concentrations of the cheese whey. For instance, at an HRT of 20 days and at 35 °C, with pH control the COD removal rose to 36%, while without pH control was much lower (15.6%). However, Garcia *et al*. [118] suggested that recirculation of reactor effluent of the methanogenesis reactor produces a dilution of the influent which allows a good system stability, without the necessity of adding alkalinity for pH control. At an OLR of 30 kg COD/(m^3 day) and at an HRT of 0.45 days in the acidification reactor and at an OLR 15 kg COD/(m^3 day) and at HRT 0.75 days in the metanogenesis reactor, higher than 99% COD removal was obtained. One way to improve the performance efficiency of digesters for high content wastewaters treatment especially the high rate anaerobic systems, such as UASB reactors or UAF, is to promote an adequate pretreatment of the substrate. Gannoun *et al*. [24] used a combined system with ecological pretreatment before the anaerobic digestion.

The pretreatment step was based on the *L. paracasei* growth on cheese whey, the fermentation of lactose into lactic acid and the precipitation of organic material after lime addition. With ecological pretreatment of cheese whey the startup has been after four weeks without any significant problem. Furthermore, the contained pollution was decreased and the BOD/COD ratio was improved from 0.5 to 0.7, making the cheese whey wastewaters more suitable for anaerobic treatment. CSTR with variable working volume was used to supply UAF with the biologically pretreated cheese whey. The stable operation of the UAF is mainly due to the liberation of ammonia from the degradation of the residual proteins in the pretreated cheese whey and the synergistic interaction between the acidogenic and methanogenic bacteria. With this combined system the highest COD removal of 98% was achieved at HRT varying from 2 to 5 days, OLR 4 g COD/(L day) and at stable operating conditions throughout the experiment [24]. Figure 2-7, illustrates the percentage of COD removal versus HRT and OLR for two phase anaerobic digestion systems which have been reported up to this point.

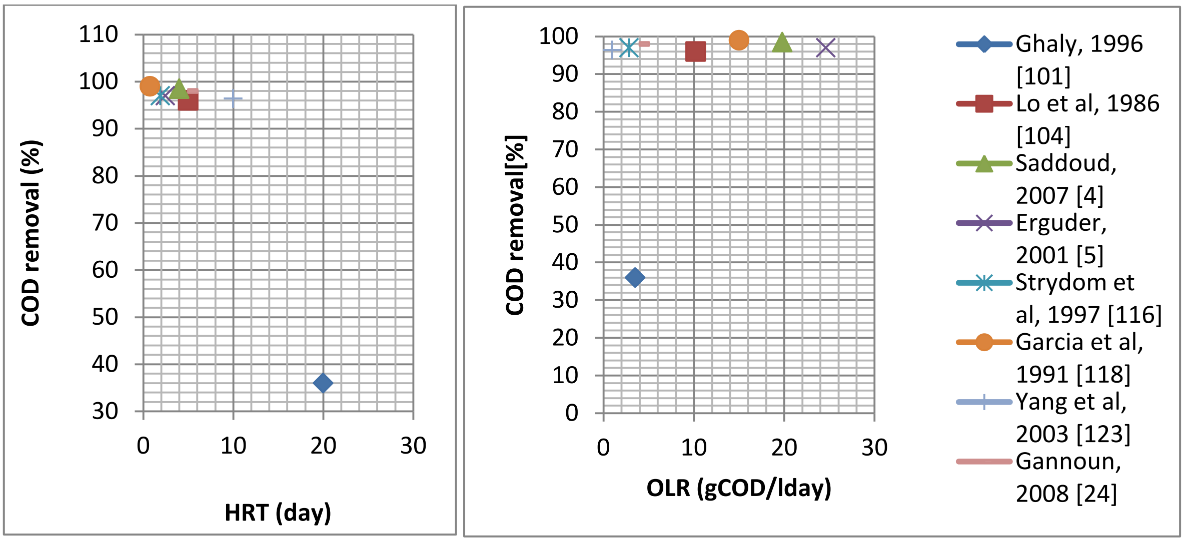


Figure 2-7 Maximum COD removal versus HRT (days) and OLR [g COD/(L day)] with the use of two phase anaerobic digestion system for CW wastewaters treatment.

Figure 2-7 shows that the COD removal rate does not vary significantly from one study to another regardless of HRT and OLR. This proves, as already mentioned, that the two phase anaerobic digestion system is an effective solution for cheese whey treatment, attaining high COD removal rates in a short HRT. Garcia *et al.* [118] succeeded in achieving the highest COD removal rate at the lowest HRT and relatively low influent organic loading. However, the value of OLR is relatively modest compared with the other studies. Saddoud *et al.* [4] obtained the next highest COD removal rate (98.5%) with the highest influent COD. It is also noteworthy the high COD removal rate was achieved by Gannoun *et al.* [24], with ecologic pretreatment reducing the wastewaters pollution content before entering the reactor for anaerobic digestion. The pretreated cheese whey which used as substrate in anaerobic digestion by UAF has quite lower organic loading (influent COD) and OLR compared to others [4, 5, 104].

2.4.3. Anaerobic/Aerobic reactors

Two steps are usually required for the complete treatment of CW wastewaters. The anaerobic degradation of the main fraction of organic matter and then the aerobic treatment of the partially treated wastewaters, in order to reduce the final organic load of the effluent and to fulfill the discharged requirements [106]. The aerobic treatment step can be provided by aerated ponds [121, 140] or using aerobic jet loop membrane reactors [23].

Malaspina *et al*. [93], reported that during an anaerobic – aerobic biological process, 98% COD reduction was achieved at an OLR of 10 g COD/(L day) in the anaerobic DUHR. Post treatment was subsequently performed with the use of SBR resulting in higher than 90% of COD and nutrients removal rates. The main objective was to reduce the high concentration of nitrogen and phosphorus still remaining in the anaerobic treated cheese whey. The nitrogen and phosphorus removals were 66–93% and 35–93 %, respectively.

Full-scale anaerobic/aerobic cheese wastewaters treatment by a system containing a grease trap, UASB type pond, aerated pond, effluent polishing pond, achieved reduction rates in BOD_5, COD, TSS, oil and grease, 98%, 96%, 98% and 99.8%, respectively [121].

Regarding the temperature of digestion, most research works on cheese whey wastewater treatment have been conducted under mesophilic and thermophilic conditions, although psychrophilic digestion can lead to lower cost treatment and can become more suitable for small scale cheese producers [107]. A preliminary study on sequential anaerobic and aerobic treatment of cheese whey wastewaters, at psychrophilic temperatures in a single digester SBR of 0.5 L volume, was carried out by Frigon *et al.* [153]. The SBR operated at cycles of 48 h, with different levels of aeration after the initial incubation of 30 h. By adding 54 mg O_2/g $COD_{influent}$ over 16 h, they achieved the best performance of the system, with soluble COD removal of 99% and a residual soluble COD of 104 ± 22 mg/L. Recently, the same research group [106], in order to reduce the cost of the investment, evaluated in a single digester the potential of psychrophilic anaerobic digestion, for the most of the biodegradable materials, followed by aerobic polishing sequence. The concept of coupling anaerobic and aerobic steps inside one digester is promising. The total cycle time (Tc) must be longer than 2 days for the efficient biodegradable fraction of cheese whey removal, at 21 °C. Moreover, the sequential anaerobic and aerobic degradation of the cheese whey wastewaters can be enhanced by improving the compartmentalization of the anaerobic and aerobic biomass inside the reactor. The integrated anaerobic and aerobic degradation in a single reactor is able to improve the overall degradation efficiency. The reported COD removal rates obtained by anaerobic/ aerobic digestion, versus HRT (days) and OLR [g COD/(L day)] are shown in Figure 2-8. It can be seen that Frigon *et al.* [106] obtained the highest COD removal at the shortest HRT and at psychrophilic conditions (20 °C) in a single digester of anaerobic and aerobic treatment. Therefore, the use of integrated reactors (anaerobic/aerobic digestion) with stacked configuration in treating high strength industrial wastewaters is advantageous in terms of minimal space requirements, low capital cost and COD removal efficiencies obtained.

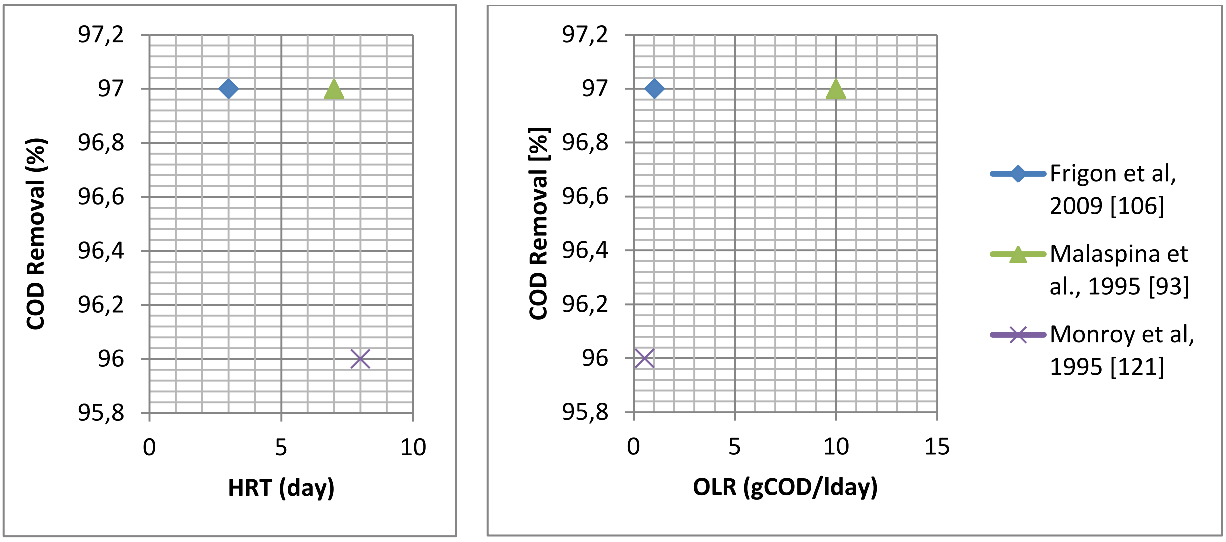


Figure 2-8 The highest COD removal versus HRT (days) and OLR [g COD/(L day)] using two steps anaerobic/aerobic digestion system for CW treatment.

However, most integrated reactors reported and described by Chan *et al*. [154] have not been applied on a large industrial scale and further research is required in order to evaluate the performance of these promising reactors on a larger scale.

2.4.4. Dairy industries using anaerobic digestion systems

Despite the fact that numerous studies have been carried out on a laboratory or pilot scale, the number known industrial scale applications of anaerobic digestion is limited. A sample of factories producing cheese and dairy products having implemented anaerobic digestion systems in order to reduce the effluents pollution load and to produce biogas covering part of their energy needs, are presented below.

HydroThane STP [155] is one of the known companies installing anaerobic digestion systems. One of its projects is the anaerobic digestion system installed in Tyras SA dairy industry (in service since 2010), which is located in Trikala, Greece. The facility is designed to treat:

- 2500 m^3/day of washwaters
- 220 m^3/day of lactose
- 90 m^3/day of by-products (market return, concentrated whey, waste sludge etc.)

The anaerobic system consists of one ECSB reactor and three SWD reactors. The system efficiency after three weeks of operation rose to 98%. The influent COD concentration is 55,000 mg/L, while after cheese whey anaerobic digestion treatment, the effluent COD concentration is 1,100 mg/L. The biogas produced is reaching at its peak the 600 Nm^3/h (almost 4 MW), covering a large part of the thermal energy requirements of the factory.

Valbio SAS [156] company is another known company in the anaerobic digestion field. One of its systems is in use in the Blackburn Cheese Dairy, in Jonquieres, Quebec, Canada, treating anaerobically 0.7 million L whey/year using a UASB reactor (Valbio’s Methacore) of 30 m^3 since 2007 (Figure 2-9).

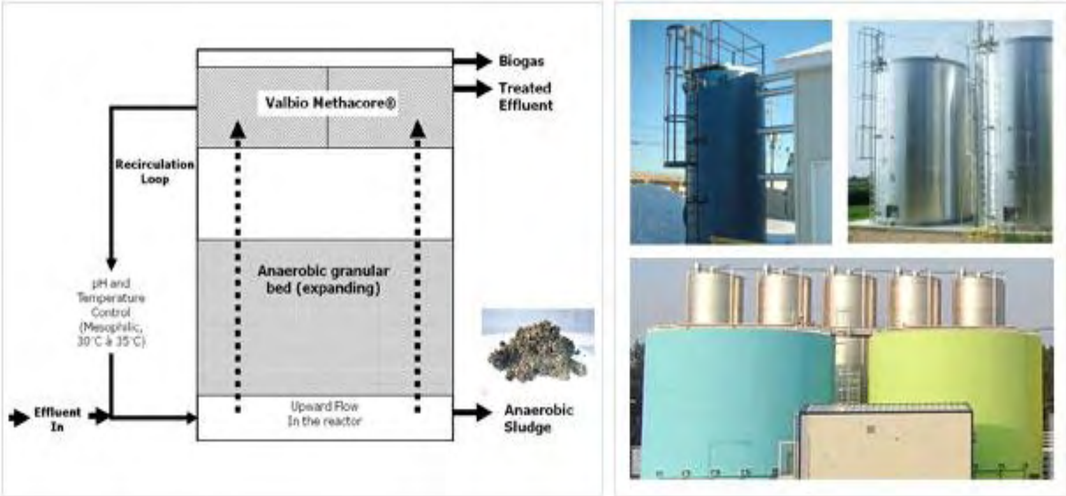


Figure 2-9 Valbio's Methacore anaerobic digestion system (fluidized bed) with anaerobic granular sludge used in different units of effluent treatment[156].

Post treatment of treated cheese whey follows the anaerobic digestion, including aerobic, nitrogen and phosphorous treatments. Through this process 28,000 m^3/year biogas (170,000 kWh/year or 580 Btu/year) are produced covering factory's energy needs, while at the same time 98% and 99% COD and BOD removal are obtained, respectively. A similar system is operated since January 2010 at Port Joli Cheese Dairy in Quebec (Canada), which treats 0.35 million L/year of cheese whey and 0.63 million L/year wash waters. The total COD of effluents is 27,000 kg/year. A sequential biological reactor for nitrogen and phosphorus treatment follows the anaerobic UASB reactor of 12 m^3 volume. The system produces 91,000 kWh/year (310 MBtu/year) biogas, achieving 95% of COD and BOD removal. At La Vachea Maillotte Cheese Dairy (La Sarre, Quebec – Canada) a similar system, operating since June 2010, treats 2.5 million L/year of cheese whey with total COD 175,000 kg/year (Figure 2-10). The produced biogas is 94,000 m^3 (640,000 kWh/year), with the COD and BOD removal being 91% and 94%, respectively.

Figure 2-10 Treatment unit of anaerobic digestion of the Dairy industry La Vachea Maillotte Cheese Dairy [156].

The same COD and BOD removal rates are achieved by anaerobic treatment of wastewaters with total COD of 127,000 kg/year (4.9 million liters washwaters per year and 1.6 million liters whey per year) in Charlevoix Dairy (Baies St Paul, Quebec – Canada). The system has been in service since March 2011. The system consists of a UASB reactor of 60 m^3, followed by aerobic post treatment and eco machine (phyto) with nitrogen and phosphorus treatment. The produced biogas is 90,000 m^3/year (equivalent to 537,000 kWh/year or 1,650 MBtu/year).

Naskeo Environment [157] is another company dealing with the installation of anaerobic digestion systems. One of its projects is the installation of valorization of the soluble industrial effluents (white water and whey) of the cheese diary of the Pays de Maroilles (North of France) using Proveo anaerobic digestion (Figure 2-11) and aerobic completion SBR systems. The average thermal power during the process is estimated 45 kW, approximately corresponding to 175 m^3/day biogas production and the average effluent purifying output is approximately 99%.

An anaerobic treatment unit has also been installed by Hager + Elsasser Company [158] at Landfrisch Molkerei, located in Austria. This project involved the treatment of whey and wastewater from cottage cheese production using anaerobic treatment in a Mixed Sludge Bed reactor which is designed to treat 180 m^3 whey/day and 11,000 kg COD/day with COD removal efficiency higher than 90% and electrical and thermal energy production of 12 and 13 MWh/d, respectively.

Montchevré is the first goat cheese manufacturer in United States (located in Belmont, WI) to use this type of wastewater treatment. The anaerobic digestion system installed by Procorp Enterprises LLC [159] has been in service since October 2010. The daily energy generation is 5,270 kWh, capable of providing power to 200 – 240 local homes.

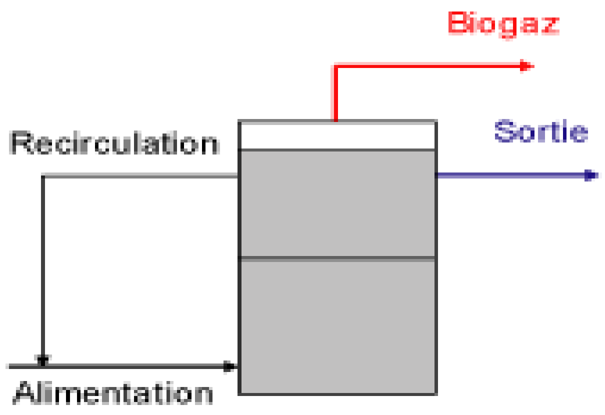


Figure 2-11 High efficiency anaerobic digestion for effluents – Proveo [157].

The above mentioned anaerobic digestion systems which have been installed in various dairy industries are summarized in the Table 2-5.

Table 2-5 Anaerobic Digestion Systems in Dairy Industries.

Company's Name	Industry	Country	Waste	Reactor	Biogas Production	Efficiency	Ref.
Hydrothane	Tyras SA Dairy	Greece	2500 m^3/day washwaters, 220 m^3/day lactose, 90 m^3/day by-products	1 ECSB & 3 SWD	600 Nm^3/h	98% COD removal	[155]
Valbio SAS	Blackburn Dairy	Jonquieres, Quebec, Canada	1,1 milion liters/year white wastewater & 0,7 million liters / year whey	UASB (30 m^3)	28,000 m^3/year	98% COD 99% BOD	[156]
	Port Joli Dairy	Saint Jean Port Joli, Quebec, Canada	0.63milion liters / year white wastewater & 0.35 million liters / year whey	UASB (12m^3)	14,000 m^3/year	95% COD 95% BOD	
	La Vache a Maillotatte Dairy	La Sarre, Quebec, Canada	2,5 million liters / year whey	UASB (60m^3)	94,000 m3/year	91% COD 94% BOD	
	Charlevoix Dairy	Baie – Saint – Paul, Quebec, Canada	2,4 milion liters / year whey	UASB (60m^3)	90,000 m^3/year	99,5% COD 99% BOD	
	Bonitrex Dairy	Asenovgra d Bulgaria	8.5 million liters / year	UASB (200m^3)	330,000 m^3/year	92% COD 92% BOD	
Naskeo Environment	Pays de Maroilles Dairy	North France	20 m^3/day	SBR	175 m^3/day	99% COD	[157]
Hager + Elsasser	Landfrisch Molkerei	Austria	180 m^3 whey/day	Mixed Sludge Bed	Electrical & Thermal Energy: 12 & 13 MWh/d respectively	90% COD	[158]

There are many economic analyses in the literature on anaerobic digestion systems for various wastewater treatments, which have proved that this process is an economically viable method for wastewater treatment. However, it is a process that requires a high investment.

The total capital costs of anaerobic digester plants may range from a few hundred thousand to a few million euros. Typically, the capital and running costs of a biogas electricity generating plant are $3,700 to 7,000/kW and $0.02/kWh, respectively [160]. Financing is therefore one of the key elements in order to ensure project viability. The financing scheme of a biogas plant project differs from country to country, but in general, low-interest, long term loans are used. Some of the feasibility studies concluded that the payback period ranges from 5 to 16 years, when these facilities operate under optimum and worst conditions, respectively. Government financial incentives for producing green energy can reduce the payback period significantly [161].

The scale of the plant is a significant factor when evaluating the economic feasibility of the anaerobic digestion systems. There is a general consensus that small-scale projects are not going to be economically feasible until there are higher net metering rates (for more details see [162]).

2.5 Conclusions from the literature review

Cheese whey is increasingly recognized as an important resource to produce value added products and “clean” energy, rather than as a waste stream with a high pollution load. The bioactive whey proteins gradually find applications not only in food products, but also in cosmetics and in the pharmaceutical sector. After recovery of proteins and other nutrients, a stream rich in lactose remains, imposing a major environmental problem that imperatively requires further treatment. Lactose is used as a component in foods and as filler or coating agent for tablets (pills) in the pharmaceutical industry. However, its use in food products is limited because of low digestibility and poor solubility (ability to crystallize). In addition, lactose is used as chemical feedstock for the production of lactose products and as substrate for production of valuable compounds by fermentation (ethanol, biogas, hydrogen etc.).

Regarding the production of biogas from cheese whey effluents the anaerobic digestion is an effective method, because of its advantages compared with other methods, such as process simplicity, high energy efficiency and low operating cost. Simultaneously with the biogas production, a high removal rate of pollution load, expressed as COD and BOD_5 removal, is obtained using various types of reactors, from simple to more complex (anaerobic filters, fixed film reactors, UASB, hybrid reactors etc.). The UASB reactors are the most common reactor configuration employed for cheese whey wastewater treatment, mainly because of their ability to treat large volumes of effluents at a relatively short period of time.

In conventional single (one phase) reactors, the acid forming and methane forming microorganisms are kept together and lead to instability and control problems. Moreover, high concentration of suspended solids in the cheese whey can also affect adversely the performance of the conventional anaerobic treatment processes, especially the most commonly used UAF. These problems can be overcome with a two-stage anaerobic digestion process, and, therefore this system should be considered as a better treatment system for cheese whey wastewater. However, the full-scale two-phase applications for dairy effluents in literature are scarce. In this type of anaerobic system the kinetic and microbiological aspects of the acidogenic reactors operating with preferably different complex type substrates should also be evaluated in more detail with focus on adverse effects that organic substrates might cause. Additionally, the subsequent methane reactor should be another substantial area for further investigation.

Nevertheless, after the anaerobic digestion process a percentage of pollution load remains in the treated effluent resulting in the necessity of subsequent processing. Anaerobic/aerobic digestion is a complete system for wastewater treatment. In addition, the use of integrated reactors (anaerobic/aerobic digestion) with stacked configuration in treating cheese whey wastewater has been proved advantageous, because of minimal space requirements, low capital cost and excellent COD removal efficiencies. Consequently, it is a very promising treatment method. Further work is required to evaluate the performance of these promising reactors on a larger scale including the biogas capture system and utilization of the suspended carrier or packing medium.

Another important factor in the anaerobic digestion is the start-up phase, which is considered to be the most critical step in the operation of an anaerobic digester. High microbial loading of inoculum material needs to be added in the mixture of biomass during the start-up stage of the anaerobic digester. So far, only few reports can be found about the inoculums and their proportion used on anaerobic digestion of cheese whey. Similarly, there is lack of information on the detailed composition of the anaerobic digestion effluent, which is very important for either direct discharge or the following treatment (anaerobic or aerobic digestion). Both of these considerations should be taken into account in the future research.

In order to evaluate the state of technology concerning the COD removal rate ability for different type of reactors and systems in use, an effort to establish a common comparative basis has been made. It was observed that most studies dealing with anaerobic digestion of cheese whey show no significant differences in the COD removal rate. The differences being mainly on HRT, OLR and influent organic loading, in which these COD removal rates were achieved. Generally, it is quite difficult to compare the systems operating in different laboratories due to differences in the anaerobic sludge characteristics and the operating parameters (temperature of reactor's operation, HRT, OLR and others). Therefore it would be useful for the future research efforts to attempt referencing where possible to similar operating conditions in order to get a clearer and more complete picture of the anaerobic digestion systems technology on a comparative basis.

In the literature, there is a very limited number of industrially-scale operating anaerobic digestion systems, especially in cheese industries. However, the increasingly stringent regulations for the wastewater disposal and the need to cover energy requirements necessitate the continuous improvement of technology and the investigation of more complex and optimized two stage systems, anaerobic/aerobic digestion reactors at full industrial scale to be applied in the near future. Moreover, it is understood that the interest has shifted to the nitrogen and phosphorus removal from dairy waste due to more strict environmental regulations and therefore current research efforts clearly seem to focus on this particular topic. Analysis and optimization of complete industrial scale anaerobic digestion systems of cheese whey (from biogas production to its combustion) is essential.

Chapter 3 Technological Background – Micro turbines

This chapter describes the main method of converting the biogas produced from anaerobic digestion treatment of cheese whey into electrical energy; thus in this chapter the characteristics of the main components and the auxiliary equipment are described.

3.1 Micro turbines

The micro turbines are miniatures of larger gas turbines engines which are started to be developed commercially in 1930s. Any micro turbine is constructed of the following main parts [163]: a turbine that transforms pressure of hot gas after it is expanded through it into motion, an alternator that generates electricity, a compressor that compresses the inlet air to high pressures, a combustor at which combustion begins between the heated compressed air and the fuel after they are mixed and burned, a recuperator which is used as a heat exchanger to transfer heat from the exhaust gas to air before it enters the combustor and a power electronics section (Figure 3-1).

Micro turbines can be divided into two types, turbo shaft and turbojet. The turbo shaft type micro turbines operate similarly to the conventional, larger gas turbine engines as described above. Their operation is usually based on the recuperated Brayton thermodynamic cycle in the case of the distributed generation applications. The turbojet type is simpler than the turbo shaft, since they do not utilize the recuperator component. The air is compressed in a centrifugal compressor, is burned in an annular type or reverse flow combustor and is partially expanded in an axial type turbine to produce power for the compressor. The hot and pressurized gases that exit the turbine are expanded to atmosphere though a convergent nozzle and produce thrust.

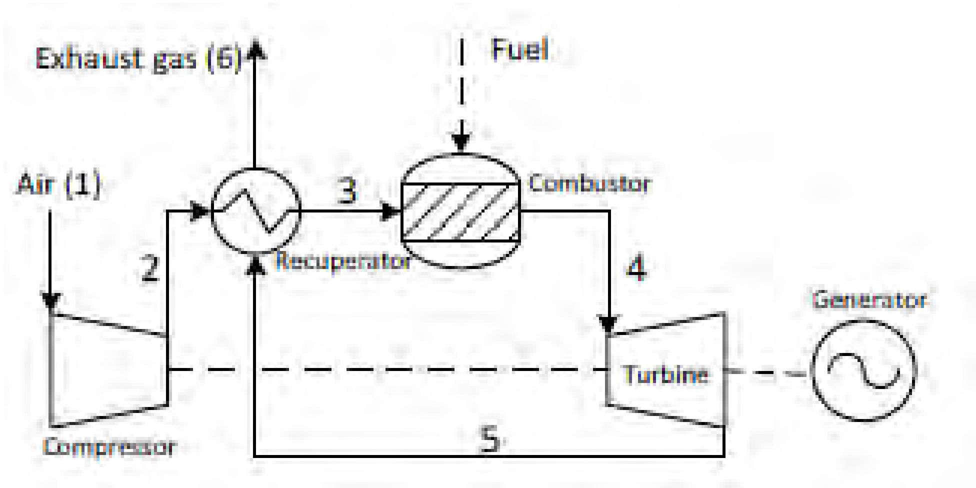


Figure 3-1 Schematic diagram of a micro turbine [164].

Micro turbines operate at very high rotational speed. The turbo shaft type can have either a single shaft or a dual shaft configuration. In the single shaft configuration the turbine generates power to drive the compressor and the generator, mounted on the same shaft. In this design, the produced electric power has a very high frequency, which is variable as the generator speed varies during the part load operation. The output power of the generator is adjusted to the desired voltage and frequency values with AC/DC/AC power controller.

On the other hand, in the dual shaft configuration the hot gases exiting from the combustor expand partially on the high pressure turbine and produce power for the compressor. Then the gases exit from the high pressure turbine and fully expand on the low pressure turbine (power turbine) and produce power for the generator. In this configuration the rotating speed of the power turbine remains constant. Some designs incorporate a gear box to reduce the shaft speed and to transmit the power to the generator. The generator produces the desired frequency without the use of a power converter. Table 3-1 presents a comparison of these two types of micro turbines.

Table 3-1 Comparison of single shaft and dual shaft micro turbines [165]

Difference item	**Single shaft**	**Dual shaft**
Speed of rotation (rpm)	50000-120000	3000 or 3600
Alternator frequency	1500-4000	50 or 60
Coupling	Turbine and alternator are directly coupled	Gear box is used to couple turbine shaft with alternator shaft
Power electronics	Power electronics section is needed to convert the high frequency AC output voltage into DC and then into AC with frequency of 50 Hz or 60 Hz	No need for power electronics
Alternator type	Usually permanent magnet synchronous generator	Usually induction generator
Maintenance	Less maintenance	Higher maintenance because of additional moving parts
Cost	Usually higher cost because of the power electronics section and type of generator used.	Lower cost
Changes of failure	Higher chances	Lower chances as gear box is more robust than complex power electronics section.
Dimensions and weight	Lower	Higher because of gear box and the lubricating system.

Micro turbines offer many potential advantages in comparison to other conversion technologies used for μCHP applications [166-168]. These include compact size and high specific power, small number of moving parts, low vibrations and noise and low maintenance requirements. All the above advantages may lead to low investment and maintenance costs, possibly short delivery time, and modularity. A major advantage of micro turbines is the ability to operate with various fuels, such as natural gas or diesel [169], biodiesel [170], pure biofuels [171] and biogas [172-175].

Although, in the literature a plethora of studies can be found dealing with applications of micro turbines fed by biogas generated in the wastewater treatment process, only Coskun et al. [14] studied the energy production through biogas utilization from whey anaerobic digestion treatment and provide information pertaining to the anaerobic digestion system. More specifically, this study conduct energy analyses of hydrogen production process driven by electricity generated from biogas resources with anaerobic digestion of whey in an industrial wastewater treatment plant in Turkey. The reactor used was UASB and its volume was 19,600 m^3. The loading capacity was changing between 1,000 and 1,200 m^3/day with 8 kg COD/m^3 day. Daily average biogas production achieves about 10,000 m^3/day and the system has a 330 kW of electricity generation capacity produced via micro turbines while simultaneously with the PEM electrolyzing system installation in the plant can achieve a 110 kg/day H_2 production. The electricity generation capacity of 330 kW is very close to the maximum electricity production of this thesis (scenario 2).

Caceres et al. [21] studied the grape pomace anaerobic digestion for biogas production and then a dynamic model of a biogas fueled micro turbine for distributed generation applications was derived. The results shown that it is possible to obtain 93,784 kWh per 1,000 tons of grape crushed. Considering that the biogas micro turbine electric efficiency is on average 33%, 30,948 kWh as electric energy can be generated. Moreover, the winery can cover up to 45% of its energy requirements for the wine – making time utilizing the grape pomace that it generates itself. Basrawi [176] investigated the appropriate electricity output of micro gas turbine cogeneration systems depending on scale of the sewage treatment plant. The performance and effectiveness of micro turbines were investigated with electrical power generating capacities of 30 kW, 65 kW and 200 kW. The system examined concern an actual middle-scale sewage treatment plant that produces monthly average of 130,000 m^3 of biogas from a population of 100,000 and the model plant was scaled down to 0.5 and 0.25. The micro turbine – cogeneration system with an output of 200 kW had the highest electrical power efficiency when heat demand of the plant does not greatly throughout the year.

Furthermore, when micro turbines are utilized in micro cogeneration applications they generate high – grade residual thermal energy (suitable for supplying a variety of building and light industrial thermal needs), and they are characterized by low emissions and relatively high efficiencies that can exceed 80% [167, 177]. On the contrary, micro turbines still exhibit low electrical efficiencies and suffer from lower output and efficiency at high ambient temperatures and at part load operating conditions. Further technological developments led to commercialization of advanced combustion turbine power generator, compressor intercooler, gas reheater and turbine blade cooling, which allowed for a higher operating temperature.

The main pollutants resulting from the operation of the micro turbines are CO, NO_x, unburned hydrocarbons and negligible amounts of SO_x [166]. CO and unburned hydrocarbons are due to the incomplete combustion process that may be due to various reasons as the bad fuel – air mixing ratio, the low residence time and bad maintenance. NO_x emissions are mainly depended on the high flame temperature and the residence time.

Chapter 4 System Description and Modeling

In this section the operating principles of the main components of the anaerobic digestion system of cheese whey treatment combined with a micro turbine for cogeneration production of heat and electricity are presented and discussed.

4.1 Methodology

In this thesis a simulation model has been developed of a biogas production system through the anaerobic digestion treatment of cheese whey wastewaters. The system model was developed using the commercially available process simulator EES [178]. The data and operational characteristics of the anaerobic digestion system used for the simulation have been selected from an anaerobic treatment system of cheese whey installed in one of the biggest dairy industries in Greece. Thus, the goal of this part of the thesis is to develop a simulation model of cheese whey wastewater anaerobic digestion treatment on a real basis.

The simulation system developed is based on the quantity of the steam delivered to the plant from the burning of the biogas produced. Two scenarios are considered here in order to extend the system for electricity generation. The first scenario refers to the incorporation of a commercially available gas micro turbine to the system for electricity production from the burning of part of the biogas produced. In this case, the selection of the appropriate micro turbine is based on obtaining the maximum electricity generation, while the plant requirements in steam are fully covered. The second scenario examines the case for the maximum electricity production without any limitation in the steam production.

The system modeling in general includes energy and exergy analysis of the system. In energy analysis, energy balances are applied to the system and its components to find the thermodynamic properties of each state and work and heat transfers within those components. Exergy analysis is a method that uses the conservation of mass and conservation of energy principles together with the second law of thermodynamics for the analysis, design and improvement of energy systems. Using this method, the locations and magnitudes of the exergy destructions and exergy losses may be found. Then, an economic analysis of these systems is carried out through the NPV method. This includes capital and installation costs and operating and maintenance costs. The objective is to maximize the economic performance of the whole plant while satisfying all design and operational constraints. Finally, a techno-economic optimization through a parametric analysis has been carried out.

4.2 EES software

For modeling a cogeneration system using biogas produced through anaerobic digestion treatment of biomass and its operation various software can be applied. Each of them has its advantages and disadvantages. Most software applicable for such a simulation is not user friendly in the way of non-defined properties of refrigerants and other media.

EES (Engineering Equation Solver) was primarily developed for mechanical engineering, thermodynamics and heat transfer at the University of Wisconsin by Dr. Beckman and Dr. Klein. It can solve various non-linear algebraic equations as well as various differential and integral equations. It finds the equations that must be solved simultaneously even when one does not follow another which makes the whole solution process easier.

It can be used for doing optimization, carrying out uncertainty analyses, and it is suitable for doing linear and non-linear regression, conversion of units and generating publication-quality plots. EES has a database of the high accuracy thermodynamic and transport properties for many substances and mathematical and thermophysical functions which enables a quick solution of problems in thermodynamics, fluid, mechanics, and heat transfer. This database is extensive.

In addition to the solving equations and providing uncertainly analyses, the EES professional version also provides animation possibilities. Graphical objects and text placed in a diagram window that have attributes such as location, size angle and color specified can be controlled with EES variables. Text items can be assigned to string variables that are specified dynamically in an EES program. As the values of these variables change, the displays in the Diagram and child Diagram windows are automatically updated [179].

EES has a large built-in data bank of thermodynamic and transport properties, which is helpful in solving problems in thermodynamics, fluid mechanics and heat transfer. EES can be used for many engineering applications; it is ideally suited for instruction in mechanical engineering courses and for the practicing engineer faced with the need for solving practical problems.

EES may be used to solve design problems in which the effects of one or more parameters must be determined. EES's parametric table, which is similar to a spreadsheet, provides this capability. The user identifies the independent variable by entering their values in the table cells. EES will calculate the values of the dependent variables. EES also provides plotting capability to display the relationship between any two variables.

EES can also be used to illustrate plant set-ups as there is a built in flow diagram function where it is possible to illustrate the components of the plant, the flows and change the input variable in order to obtain other costs and gas yields for example.

4.3 System layout

Figure 4-1 depicts the flow diagram of the cogeneration system. The anaerobic plant has been designed to treat 150 m^3/day of whey, produced with the use of ultrafiltration membranes. The introduction of the ultrafiltration membranes in the cheese and the cream cheese making processes is due to the need to minimize the production cost.

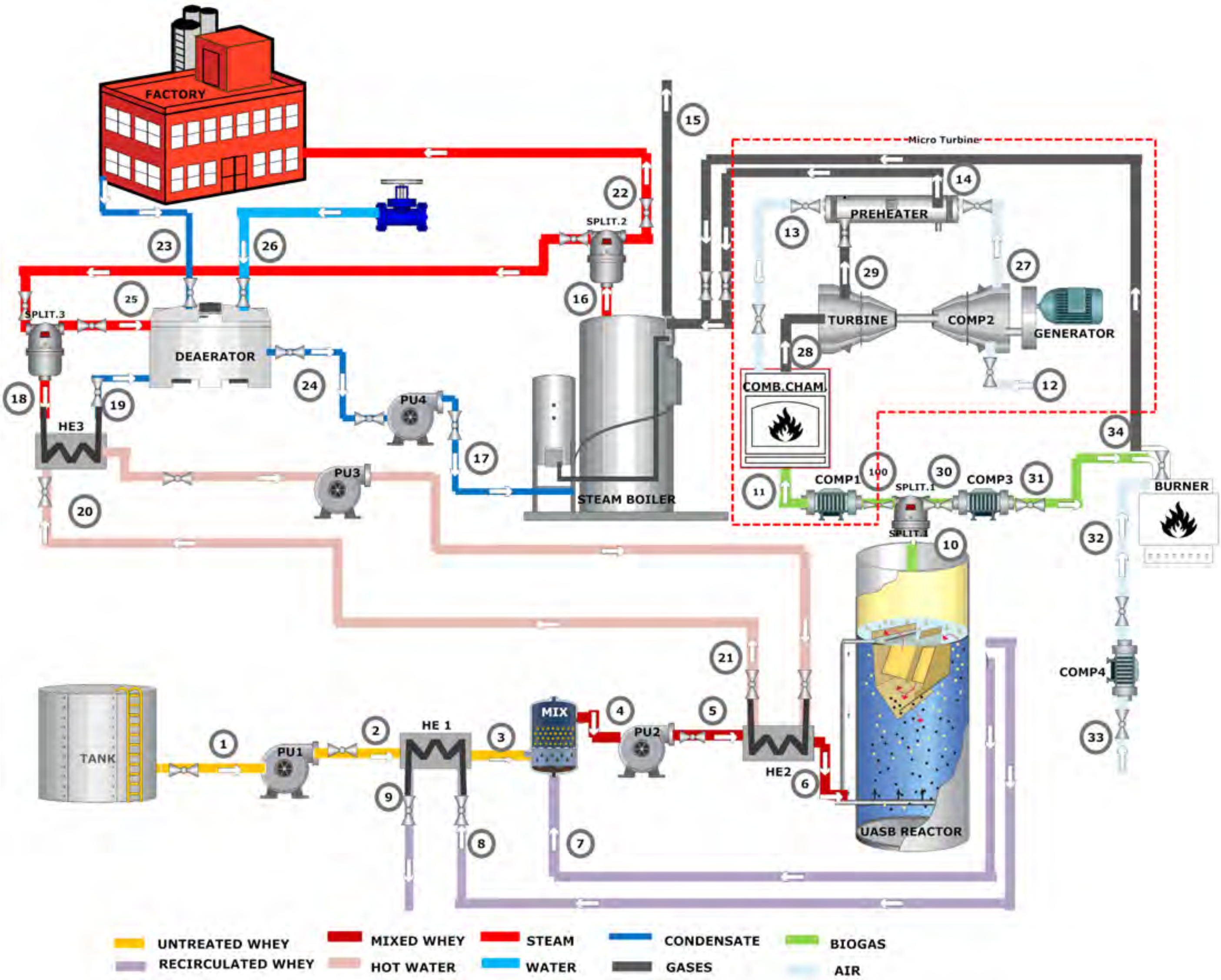


Figure 4-1 Flow chart of the system examined.

The ultrafiltration membranes 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 block molecules of proteins and fats, as it is illustrated schematically in Figure 4-2. Thus, the permeate obtained, which is whey, consists mainly of water by 95% and lactose ($C_{12}H_{22}O_{11}$) by 5%, while protein content is minimized to less than 0.1% [13, 60].

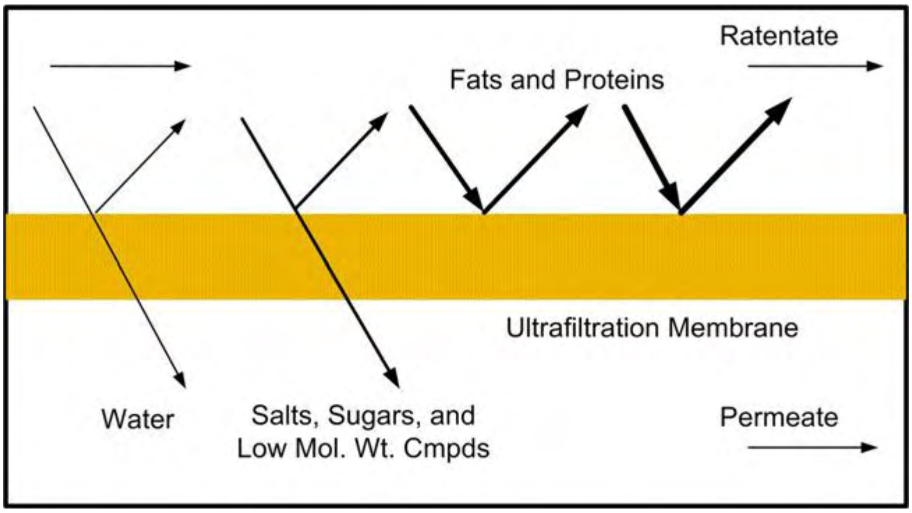


Figure 4-2 Ultra –filtration schematic process [13].

The COD of cheese whey has been measured equal to about 60,000 mg/L. The composition and the characteristics of the cheese whey considered in this work are presented in Table 4-1 (as given by the dairy industry).

Table 4-1 Composition and characteristics of cheese whey.

Constituent	Percentage (%)
Water	94-95
Protein	0.8-1.0
Lactose	4.5-5.0
Fat	<0.1
Minerals	<0.1
pH	4.5-5

The filtered whey is collected at ambient conditions in a stainless steel tank, having a capacity of 125 m^3, which serves as a buffer tank. Then it is pumped with the use of a centrifugal pump (PU1) at a constant flow of 6.25 m^3/hr to the reactor (UASB REACTOR). The untreated whey is heated in the first heat exchanger (HE1) from the treated whey, which exits the reactor and then it is mixed with a recirculated whey 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 after it passes a second heat exchanger (HE2) where it is heated to the desired temperature of 35 °C. The type of the reactor in this system is of type UASB (Figure 4-3) and its volume is about of 1,200m^3. The choice was based on the fact that UASB is a reactor where high organic removal efficiencies are aobtained with quite low HRT of the waste in the reactor, as it has been previously discussed in Chapter 2.

The heating in the second heat exchanger (HE2) is done using hot water heated by the steam produced from the biogas combustion. As the mixed whey passes upwards throughout the reactor, the microorganisms attack to the feed while generating biogas. The biogas rises through the liquid emerging in the gas – liquid interface just beneath the membrane cover. An insulated floating membrane cover is used to collect biogas and to minimize the heat loss. The biogas produced in the reactor is collected from the top and then it is stored in a tank.

In this thesis it is assumed that the whole biogas produced in the UASB reactor is directly supplied to the CHP unit with a constant rate. Consequently, the tank for the biogas storing is not taken into account for the model development.

In the existing AD system which operates in the dairy industry there is a burner where the biogas is burned with ambient air in order to produce only steam through steam boiler to cover the thermal needs of the plant.

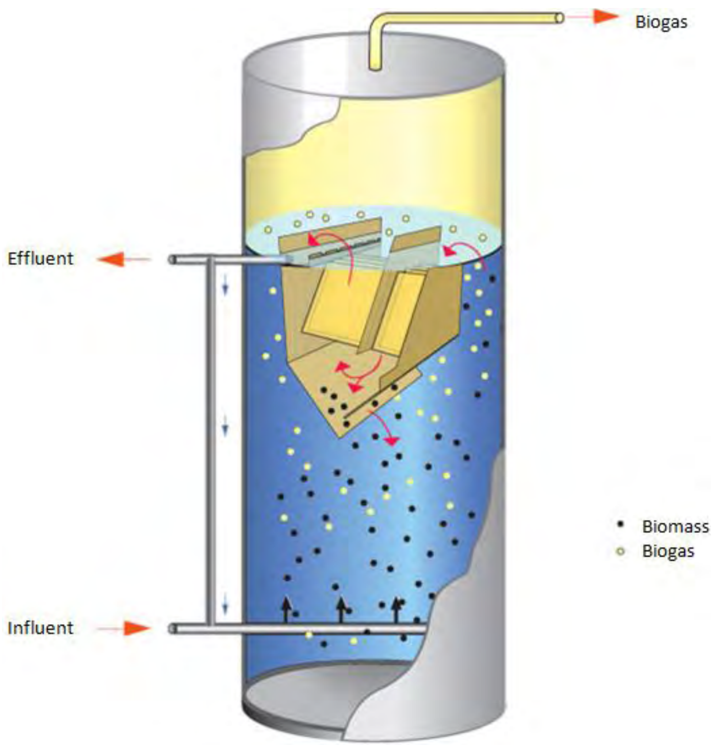


Figure 4-3 UASB reactor scheme [180]

In the first scenario examined in this thesis the biogas collected from the top of the reactor is directed to a splitter (SPLIT 1), where it separates into two parts: one part is directed to the burner for steam production and the other to the micro turbine for electricity production. The splitter solution was adopted because the analysis performed suggested that both burner and micro turbine are required in order to meet the existing standards and requirements of the plant, such as the biogas production ability and the steam consumption. The choice of the most suitable commercial available micro turbine is extensively discussed. The gases from the burner accompanied with the gases from the micro turbine are directed to the steam boiler and then are exhausted to the environment in a low temperature. 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 used 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 through the addition of fresh water.

In the second scenario, the goal is the maximum electricity production without any limitation regarding the steam production. In this situation the system configuration is much simpler than in the first scenario, as the entire quantity of the biogas produced and collected from the top of the reactor is directed only to the micro turbine. The selection of the most suitable micro turbine among the commercially available micro turbines is also examined. Similar to the first scenario, the gases produced from the micro turbine are also directed to the steam boiler and then are exhausted to the environment in a low temperature. 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 used 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. Also in this case, the rest of the quantity needed is covered through the addition of fresh water.

4.4 Theory for the System Modeling

Thermodynamic models are developed for the Kalina and LiBr/H_2O cycles [181]. In these models, each component of the system is treated as a control volume and the principle of mass conservation and the first and second laws of thermodynamics are applied to the component. In order to simplify the system analysis the following assumptions have been made:

- Steady state operation is considered.
- The reference environment is considered to be at 1.013 bar and 25 °C.
- The untreated whey is consisted only of water (95%) and lactose (5%).
- The whole biogas produced is directly supplied to the CHP system with a constant rate.
- Ideal - gas principles apply for the air, combustion products and biogas.
- Whey which is in liquid form (untreated, recirculated or treated) is incompressible.
- The combustion reactions are complete.
- There are no gas leakages from the system.
- The only heat losses in the system are from the burner and combustion chamber.
- The turbine operates at a full load.
- In the steam boiler are considered no heat losses.

- The distributions of temperature, pressure and gas compositions are neglected.
- The fuel is considered desulfurized.
- The fuel compression work is not taken into account.
- 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.
- 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.

4.4.1 Thermodynamic properties

The Thermodynamic Properties of Whey (untreated, recirculated and treated) are calculated by the following relations:

- The specific enthalpy of whey is given by:

$$\bar{h} = x_{H_2O} \cdot \bar{h}_{H_2O} + x_s \cdot \bar{h}_s \quad (1)$$

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

$$\bar{h}_{H_2O}(T, P) = \bar{h}_{f,H_2O}(T) + \bar{v}_{f,H_2O} \cdot [P - P_{sat}(T)] \quad (2)$$

The enthalpy, $\bar{h}_s$, of the solute 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 the examined system.

- The specific entropy of whey is given by:

$$\bar{s} = x_{H_2O} \cdot \bar{s}_{H_2O} + x_s \cdot \bar{s}_s \tag{3}$$

- The entropy of water for any temperature and pressure can be estimated according to the following relation:

$$\bar{s}_{H_2O}(T, P) = \bar{s}_{f,H_2O}(T) \tag{4}$$

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

Regarding the thermodynamic properties of the biogas and the air calculation the following considerations apply:

It is assumed that both of them biogas and air are mixtures of ideal gases. So, the thermodynamic properties of both mixtures are given by the following:

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

$$P_k = \frac{n_k}{n} \cdot P \tag{5}$$

- The enthalpy of the mixture is taken by:

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

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 taken by:

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

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.

In addition the mass flows can be calculated according to the following equation:

$$\dot{m} = \dot{Q} \cdot d \quad (8)$$

- The mass balance equation

The conservation of mass principle is a fundamental principle in analyzing any thermodynamic systems. This principle is defined for a control volume, as given by the following equation:

$$\sum_k \dot{m}_{inlet} - \sum_k \dot{m}_{outlet} = 0 \quad (9)$$

4.4.2 Pipes

The pipes used in the plant examined are considered of stainless steel. Various diameters pipes from DN 50 mm to DN 200 mm and various types of parts such as tau, angles etc. are used. In order to determine the pressure loss or flow rate through pipes knowledge of the friction between the fluid and the pipe is required. The equation of Colebrook – White is used in order to determine the friction factor. This equation was developed taking into account experimental results for the flow through both smooth and rough pipe [182]. The Colebrook equation is taken by:

$$\frac{1}{\sqrt{f}} = -2 * \log\left(\frac{\frac{k_S}{D}}{3.7} + \frac{2.51}{Re*\sqrt{f}}\right) \tag{10}$$

where the k_s is roughness of pipe and D the pipe diameter.

The definition of the Reynolds number, Re, is as follows:

$$Re = \frac{u*D}{\nu} \tag{11}$$

where u is the mean fluid velocity and ν the kinematic viscosity

Thus the pressure drop for the various pipe types used in the modeling can be determined by:

$$\frac{\Delta P}{\rho} = f * \left(\frac{2*L}{D}\right) * \left(\frac{4*Q}{\pi*D^2}\right)^2 \tag{12}$$

In this equation ΔP is the pressure drop, ρ is the density of the fluid, D is the hydraulic diameter of the pipe.

4.4.3 Heat exchangers

Heat exchangers are devices where two moving fluid streams (Figure 4-4) exchange heat without mixing. The outlet conditions can be estimated by taking into account the following relations for the mass balances:

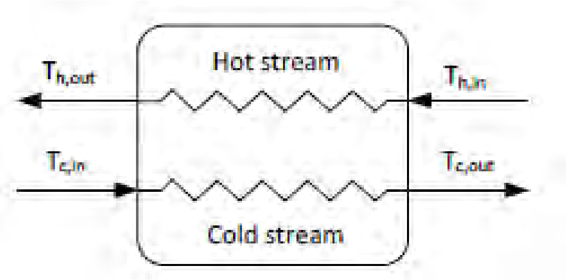


Figure 4-4 Counter flow heat exchanger

$$\dot{m}_{hot,inlet} = \dot{m}_{hot,outlet} \quad (13)$$

$$\dot{m}_{cold,inlet} = \dot{m}_{cold,outlet} \quad (14)$$

$$\dot{m}_{hot}\left(h_{hot,inlet} - h_{hot,outlet}\right) = \dot{m}_{cold}\left(h_{cold,outlet} - h_{cold,inlet}\right) = Q \quad (15)$$

4.4.4 Mixing unit

The mixing unit is used to premix the untreated whey with recirculated whey. For the modeling of the mixing unit of the system, the conservation of mass requires that the sum of the mass flow rates into the mixing unit equal the mass flow rate out of the mixing unit. The continuity equation and energy balance are expressed by following equations:

$$\sum \dot{m}_{inlet} - \dot{m}_{outlet} = 0 \text{ and } \sum \dot{m}_{inlet} h_{inlet} - \dot{m}_{outlet} h_{outlet} = 0 \quad (16)$$

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

$$T_4 = \frac{\dot{m}_3 \cdot T_3 + \dot{m}_7 \cdot T_7}{\dot{m}_3 + \dot{m}_7} \quad (17)$$

4.4.5 Reactor dimensioning and methane produced during anaerobic digestion

According to Metcalf and Eddy [183], the volume of the reactor is given by the following equation:

$$V = HRT * \dot{Q} \tag{18}$$

Taken into account that the data listed in the previous chapter and obtained from the factory, the volume of the reactor is calculated 1,200 m^3 with an upflow velocity of 1 m/hr.

The theoretical amount of CH_4 produced in anaerobic digestion can be calculated by assuming that the removal of COD is the amount of oxygen needed to oxidize CH_4 to H_2O and CO_2 [13, 183] as shown below:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{19}$$

From equation (18) the required oxygen needed, per mole of CH_4 produced, is 2 × 32 g O_2/mol CH_4 = 64 g O_2/mol CH_4. At standard conditions (0 °C and 1 atm) the volume of CH_4 is 22.414 m^3, so the CH_4 equivalent of COD converted under anaerobic conditions is 22.414/64 = 0.35 m^3 CH_4/g COD removed. At 35 °C and 1 atm, the volume of 1 mole of methane is 25.29 m^3; the production of CH_4 is 25.29/64 = 0.4 m^3 CH_4/kg COD removed. Thus, the volumetric flow of methane is calculated by:

$$\dot{Q}_{CH4} = \dot{Q}_{whey} * COD_{content} * COD_{content-efficiency} * 0.4\,\frac{m^3 CH_4}{Kg\;COD_{removed}} \tag{20}$$

The treated whey exits the reactor with a COD of 1200 mg/L, which corresponds to a COD removal efficiency of 98%. The CH_4 content in biogas is considered equal to 60% and the rest is CO_2. So, given the densities of CH_4 and CO_2 at the state of the UASB reactor outlet, the mass flow of biogas is calculated.

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

$$TOC_1 = \frac{\dot{m}_1 * X_{s,1}}{MB_{s,1}} \times A_{r,c} \times (\text{Carbon Atoms in Lactose}) \quad (21)$$

$$TOC_{10} = \frac{\dot{m}_{CH_4}}{M_{CH_4}} \times (\text{Carbon Atoms in } CH_4) + \frac{\dot{m}_{CO_2}}{M_{CO_2}} \times (\text{Carbon Atoms in } CO_2) \quad (22)$$

From the equations above, it can be found that $TOC_{biogas}/TOC_{CW,inlet}$ = 90%. The rest of TOC goes to the biomass and the treated flow and it is assumed that 5% of $TOC_{CW,inlet}$ goes to the treated flow and the rest 5% to the biomass.

A relation between TOC, chemical exergy and free energy of organic matter in wastewater is presented in Tai et al. [184]. 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, the following equations are resulted:

$$\bar{h}_{s,8} = \bar{h}_{s,7} = 0.05\bar{h}_{s,1} \quad (23)$$

$$\bar{s}_{s,8} = \bar{s}_{s,7} = 0.05\bar{s}_{s,1} \quad (24)$$

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

$$C_{12}H_{22}O_{11} \rightarrow A \cdot CH_4 + B \cdot CO_2 + C_aH_bO_c \quad (25)$$

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:

$$\frac{\dot{m}_1 * x_{s,1}}{MB_{Lactose}} = \frac{\dot{m}_8 * x_{s,8}}{MB_{s,8}} \tag{26}$$

where

$$x_{s,8} = \frac{\dot{m}_8 * X_{s,8}}{MB_{s,8}} \tag{27}$$

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

$$2 \cdot \dot{m}_{s,8} = \dot{m}_{s,1} - \dot{m}_{10} \tag{28}$$

4.4.6 Biogas & Air compressors

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

$$n_{sc} = \frac{h_{outlet,isentropic} - h_{inlet}}{h_{outlet} - h_{inlet}} \tag{29}$$

4.4.7 Biogas combustion in the burner

The biogas is mixed with the air and the mixture is burned in order to produce thermal energy for use to cover the thermal needs of the plant. As it has been referred in the assumptions the combustion process is considered complete and the burner adiabatic. The combustion equation of the biogas is described by the following chemical reaction:

$$\lambda * [0.6CH_4 + 0.4CO_2] + [0.7748N_2 + 0.2059O_2 + 0.0003CO_2 + 0.019H_2 \rightarrow (1 + \lambda)[n_{N_2}N_2 + n_{O_2}O_2 + n_{CO_2}CO_2 + n_{H_2O}H_2O \tag{30}$$

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

$$n_{N_2} = \frac{0.7748}{1+\lambda} \tag{31}$$

$$n_{CO_2} = \frac{0.0003+\lambda}{1+\lambda} \tag{32}$$

$$n_{H_2O} = \frac{0.019+1.2*\lambda}{1+\lambda} \tag{33}$$

$$n_{O_2} = \frac{0.2059-1.2*\lambda}{1+\lambda} \tag{34}$$

The molar fraction of O_2 has been considered equal to 0.04. If λ* corresponds to complete combustion, i.e. n_{O2}=0, the excess air used for the combustions is given by:

$$ExcessAir = \frac{\lambda^*}{\lambda} \tag{35}$$

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

$$-0.02 * \lambda * \mathrm{LHV} + \overline{h_{air}} + \lambda * \overline{h_{biogas}} - (\lambda + 1) * \overline{h_{gases}} = 0 \tag{36}$$

4.4.8 Micro turbine

Micro turbines are composed of four major components as air compressor, combustion chamber, gas turbine and recuperator.

According to Stamatis [185] the turbomachinery components (compressor, turbine) could be modeled through following equations:

<u>Definition equations</u>: These are the pressure ratio and isentropic efficiency relations for the compressor (Eq.36) and turbine (Eq. 37) components.

$$\left\{PR_c = \frac{P_{out}}{P_{in}}, n_{is,c} = \frac{h_{out,is}-h_{in}}{h_{out}-h_{in}}\right. \tag{37}$$

$$\left\{ PR_t = \frac{P_{in}}{P_{out}}, n_{is,t} = \frac{h_{in} - h_{out}}{h_{in} - h_{out,is}} \right. \quad (38)$$

Conservation equations: The mass balance and the energy balance are taken by the following equations respectively:

$$\dot{m}_{out} - \dot{m}_{in} = 0 \quad (39)$$

$$\dot{Q} - P = h_{out}\dot{m}_{out} - h_{in}\dot{m}_{in} \quad (40)$$

The compressor and turbine devices are considered adiabatic, so the heat transfer rate $\dot{Q}$ is equal to zero. Also, the power output P is negative in case of the compressor and positive in case of the turbine.

4.4.8.1 Combustion Chamber

In the combustion chamber of the micro turbine the part of the biogas produced from the splitter (first scenario) or the whole produced biogas (second scenario) is burned with air. The gases produced are used to cover part of the plant thermal needs. In the first scenario examined the produced gases from the burner are mixed with the gases from the micro turbine and lead to steam boiler in order to cover the plant thermal needs.

In the second scenario the gases produced also lead to the steam boiler in order to cover part of the plant thermal needs. The outlet properties of the combustion chamber are a function of air mass flow rate, biogas lower heating value (LHV) and combustion efficiency and are related as follows:

$$\dot{m}_{air}h_{air} + \dot{m}_{biogas}LHV = \dot{m}_{gases}h_{gases} + (1 - n_{cc})\dot{m}_{biogas}LHV \quad (41)$$

The combustion chamber outlet pressure is defined by considering a pressure drop across the combustion chamber as follows:

$$\frac{P_{gases}}{P_{biogas}} = 1 - \Delta P_{cc} \qquad (42)$$

Where ΔP_{cc} is the pressure loss across the combustion chamber and n_{cc} is the combustion effieciency.

The combustion reaction occurring and its species coefficients can be expressed with the same relations expressed above in the burner description.

4.4.8.2 Gas Turbine

The isentropic efficiency of the gas turbine can be expressed by:

$$n_{Sturb} = \frac{h_{outlet} - h_{inlet}}{h_{outlet,isentropic} - h_{inlet}} \qquad (43)$$

The gas turbine mass flow rate is calculated as:

$$\dot{m}_{gases} = \dot{m}_{biogas} + \dot{m}_{air} \qquad (44)$$

Here, the energy balance is obtained through the following equation:

$$-\dot{W}_{GT} + \frac{\dot{m_{air}}}{MB_{air}} * (h_{air\ comp\ ,outlet} - h_{air\ comp\ ,inlet}) + \frac{\dot{m_{gases}}}{MB_{gases}} * \left(h_{gases\ turb\ ,outlet} - hgases\ turb\ ,\ inlet = 0 \qquad (45)\right.$$

4.4.8.3 Recuperator

The recuperator is a heat exchanger which is used to recover heat from the hot exhaust gases. The heat is supplied to the compressed air before it enters into the combustion chamber contributing to lower biogas consumption.

For a counter flow heat exchanger the mass balance between the two fluids is taken under the following equation:

$$\dot{Q} = \dot{m}_{cold} C_{pcold} (T_{cold,out} - T_{cold,in}) = \dot{m}_{hot} C_{phot} (T_{hot,in} - T_{hot,out}) \quad (46)$$

4.4.9 Steam boiler

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 losses taking place:

- For the first scenario examined the gases from the burner accompanied by the gases from the micro turbine are leaded to the steam boiler for steam production. The energy and mass balances are described by the following equations:

$$\dot{m}_{gases\ turb,inlet} * h_{gases\ turb,inlet} + \dot{m}_{gases\ burn,inlet} * h_{gases\ burn,inlet} + \dot{m}_{condensate,inlet} * h_{condensate,inlet} = \dot{m}_{gases,outlet} * h_{gases,outlet} + \dot{m}_{steam,outlet} * h_{steam,outlet} \quad (47)$$

where

$$\dot{m}_{steam,outlet} = \dot{m}_{condensate,inlet} \quad (48)$$

$$\dot{m}_{gases,outlet} = \dot{m}_{gases\ turb,inlet} + \dot{m}_{gases\ burn,inlet} \quad (49)$$

furthermore, the new composition of the gases in this state has been calculated from the above relations:

$$n_{gases\ outlet} = n_{turb\ gases} + n_{burn\ gases} \tag{50}$$

$$x_{gases\ outlet,O2} = \frac{n_{turb\ gases,O2} + n_{burn\ gases,O2}}{n_{gases\ outlet}} \tag{51}$$

$$x_{gases\ outlet,CO2} = \frac{n_{turb\ gases,CO2} + n_{burn\ gases,CO2}}{n_{gases\ outlet}} \tag{52}$$

$$x_{gases\ outlet,N2} = \frac{n_{turb\ gases,N2} + n_{burn\ gases,N2}}{n_{gases\ outlet}} \tag{53}$$

$$x_{gases\ outlet,H2O} = \frac{n_{turb\ gases,H2O} + n_{burn\ gases,H2O}}{n_{gases\ outlet}} \tag{54}$$

- For the second scenario examined the gases from the micro turbine are guided to the steam boiler for steam production. The energy and mass balances are described by the following relations:

$$\dot{m}_{gases\ turb,inlet} * h_{gases\ turb,inlet} + \dot{m}_{condensate,inlet} * h_{condensate,inlet} = \dot{m}_{gases,outlet} * h_{gases,outlet} + \dot{m}_{steam,outlet} * h_{steam,outlet} \tag{55}$$

where

$$\dot{m}_{steam,outlet} = \dot{m}_{condensate,inlet} \tag{56}$$

$$\dot{m}_{gases,outlet} = \dot{m}_{gases\ turb,inlet} \tag{57}$$

4.4.10 Total power production of the modeled system

In the approach of the first scenario, the total spent power in the system resulted mainly from the pumps and compressors movement and is taken by the following equation:

$$W_{total,\ spent} = W_{P1} + W_{P2} + W_{P3} + W_{P4} + W_{comp1} + W_{comp3} + W_{comp4} \tag{58}$$

The power of the micro turbine is taken by:

$$W_{MT} = W_{comp2} + W_{turb} \tag{59}$$

The net output power can be expressed as:

$$W_{net} = W_{total,spent} - W_{MT} \tag{60}$$

In the second scenario, the total spent power in the system is calculated by:

$$W_{total,\ spent} = W_{P1} + W_{P2} + W_{P3} + W_{P4} + W_{comp1} \tag{61}$$

and the power of the micro turbine used and the net output power are calculated as presented above in the first approach.

4.5 General approach for the system modeling

The model of the system as described by the equations above could be represented by a general relation of the form:

$$Y = f(X, u)$$

where,

$Y = [\dot{W}, \dot{m}_{steam}, y_i]^T$, y_i: thermodynamic variable (p, T, h, s, m) at state i

$\dot{m}_{steam}$: steam production

$\dot{W}$: power production

$X = [x_j]^T$, x_j: device j (pumps, compressors, heat exchangers etc) parameter (efficiencies, pressure ratios etc)

$u = [\,r\ \ \dot{m}_{CW}, u_k]^T$, u_k: input parameter (ambient conditions, compositions etc)

r: amount of the biogas guided from the splitter to the MGT

As it has been referred above, with the use of the model two scenarios are examined in this study.

The first scenario concerns the selection of the suitable commercially available micro turbine for matching the existing system requirements and production capacity with the specifications of the micro turbine as given by the manufacturers.

In the second scenario was investigated the case of variant steam requirement, the target being the highest possible electric power production.

These two scenarios are expressed as optimization problems with the use of the previous formalism:

Maximize $\dot{W}$ under the following constraints:

$\dot{W} \in \{\dot{W}_{1,}\dot{W}_{2,}\dot{W}_{n,}\}$ (kW) where $\dot{W}_i$ power rate of commercially available micro turbines,

$y_l = z_l$, where z_l: MGT specifications (exhaust gas temperature etc)

$\dot{m}_{steam} = \text{constant (scenario 1)}$or $\dot{m}_{steam} \geq 0$ (scenario 2)

Chapter 5 Analysis of a cogeneration CW AD treatment system based on existing components

Based on the relations in Chapter 4, a model of a cogeneration of heat and electricity system through the anaerobic digestion treatment of cheese whey is developed based on existing devices. It can be seen from a literature review that there are many papers on whey anaerobic digestion systems focusing mainly on the parameters which affect the process of anaerobic digestion, the COD removal and the biogas production rate (for more details see [9]). However, the number of studies on the utilization of biogas systems to produce energy (heat and electricity) from whey is limited [13, 14] in comparison to other waste types [15-21]. In this chapter two approaches are examined. In the first scenario, the target is the selection of the most suitable micro turbine to match with the anaerobic digestion treatment system of cheese whey based on existing operational data, respecting the constraints of the system and the technical specifications and features of the chosen micro turbine as given by the manufacturer.

In the second scenario was investigated the case of the highest possible electric power production. Thus, the most suitable micro turbine for incorporation to the modeled cheese whey anaerobic digestion treatment system is obtained.

5.1 Model development for the first scenario examined

The model developed for the anaerobic digestion treatment system as it has been referred in previous chapters is based on existing devices. The operational data for the modeling has been taken from a corresponding plant which is operating in cheese making industry in Greece. Thus, certain limitations and requirements are arisen such as the quantity of the cheese whey for anaerobic digestion treatment and following the amount of the biogas produced, the quantity of the steam produced which is used in order to cover the plant thermal needs and other operational characteristics such as the temperature and pressure of the cheese whey in the tanks etc.

These limitations and requirements have to be taken into account during the selection of the most suitable micro turbine. In order to select the most suitable micro turbine for its coupling into the system five commercially available micro turbines have been examined. The technical specifications and features of the micro turbines as these are given by the manufacturers constitute further parameters which should be also respected during the model development.

The five engines were selected: C30 and C60 manufactured from Capstone Turbine Corp., the Parallon 75 kW, the T100 from Turbec and the Ingersoll Rand's MT250. The characteristics of each engine are presented in Table 5-1. Thus, five different approaches of the system design have been obtained and compared in order to reach in the most efficiently coupling of micro turbine and anaerobic digestion treatment system.

Table 5-1 Parameters of micro turbines at design point [186].

Parameters	Capstone C30	Capstone C60	Parallon 75	Turbec T100	Ingersoll Rand MT250*
Rotational speed (rpm)	96,000	96,000	65,000	70,000	45,000
Pressure ratio	3.6	4.8	3.5	4.5	3.5
Air flow (kg/s)	0.31	0.48	0.75	0.79	0.79
Turbine inlet temperature (K)	1117	1228	1148	1223	1125
Turbine exit temperature (K)	866	908	912	923	922
Exhaust gas temperature (K)	546	578	511	543	515
Compressor isentropic efficiency	0.83	0.77	0.78	0.78	0.79
Turbine isentropic efficiency	0.85	0.85	0.84	0.83	0.82
Electric power (kW)	30	60	75	100	250
Electric efficiency	0.26	0.28	0.285	0.30	0.30

*[187, 188]

In each approach, 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 approach of the system was carried out by checking the values resulting for various parameters such as the steam mass flow for factory energy needs, the electricity capacity, the turbine exit temperature, the exhaust gas temperature, the temperature of the compressed air. One of the most important factors which is predicted and affected significantly the system operation and therefore the outputs from the modeling is the amount of the biogas separated through the splitter and guided to the micro turbine and to the burner. The predicted design point's results are summarized in Table 5-2.

Table 5-2 Results from five different approaches of the modeling system.

Micro turbine	Biogas guided to MT(kg/hr)	Electricity power production (kW)*	Amount of steam produced (kg/hr)
C30	18.7	30.12	1701.4
C60	36.7	59.14	1644.2
Parallon 75	42.7	74.60	1617.1
T100	**57.7**	**100.8**	**1566.6**
MT250	151.7	250.17	1241.8

It is obvious that the total power produced increases significantly with the size of the micro turbine. On the other hand, the total steam production is considerably decreased with the increasing of the biogas quantity that is fed to the micro turbine, as expected. The results shown that the selected engines can be combined with the cheese whey anaerobic digestion treatment system except the MT250 which is not satisfied the requirements in steam production. However, smaller size of the micro turbines contributes to lower values of electricity and to higher values of steam production. Thus, from the above analysis resulting that the best solution for the micro turbine selection is the engine model T100.

5.1.1 Analysis results

The single shaft micro turbine T100 by Turbec manufacturer constitutes an excellent solution for the extension of the cheese whey anaerobic digestion treatment system with significant electricity generation. From the analysis carried out in the frame of the first scenario examined, it is concluded that the resulting system is quite marginal without any alternative solution in terms of the micro turbine selection due to the limitations referred above and especially due to the required amount of the steam production. The values of the input parameters to the modeling of the micro turbine are presented in Table 5-3:

Table 5-3 Parameters of micro turbine T100 at design point.

Name	Parameters	Values
Micro turbine efficiency	n_{MT}	0.83
Compressor efficiency	n_{sc}	0.78
Air temperature at the output of recuperator (K)	T_{13}	900
Gases temperature of the MT combustion chamber (K)	T_{28}	1223
Compressor Pressure ratio	PR_c	4.5

As it can be seen in Table 5-4, there is a good agreement between expected and calculated performance parameters for the micro turbine T100 at design points conditions.

Table 5-4 Micro turbine model validation

Name	Parameters	Manufacturer	Calculated	Error (%)
Electricity capacity (kW)	W_{MGT}	100	100.8	0.8
MT Exhaust Temp (K)	T_{14}	543	542.44	-0.11
Turbine Exhaust gas (K)	T_{29}	923	924.34	0.15
Compressed air (K)	T_{27}	487.15	497.37	2.09

In this point, the mass flow, temperature, enthalpy, entropy and fluid condition at each state of the system are given in Table 5-5.

5.2 Model development for the second scenario examined

In this scenario, as it has been referred in previous chapter (Chapter 4), the maximum production of electricity with no constraints on the steam production is studied. So, in this case the study starts opposite to the first scenario. More specifically, the target was to calculate the maximum electricity which can be obtained of the whole biogas produced and then to select the most suitable micro turbine.

In this case there is not a splitter component and the whole biogas produced by cheese whey anaerobic digestion treatment is guided directly to the micro turbine. The power production has been calculated by:

$$-\dot{Q}_{MT} + \frac{\dot{m}_{12}}{MB_{air}}(h_{27} - h_{12}) + \frac{\dot{m}_{28}}{MB_{gases}}(h_{29} - h_{28}) = 0 \qquad (62)$$

Table 5-5 Mass flow, pressure, temperature, enthalpy, entropy and fluid condition at each state of the system.

State	Fluid Condition	$\dot{m}$(kg/hr)	P(bar)	T(K)	h(kJ/kmol)	s(kJ/kmol)
1	Untreated Whey	6341.7	1.013	298.15	-8994	14.862
2	Untreated Whey	6341.7	1.569	298.15	-8992	14.862
3	Untreated Whey	6341.7	1.038	302.15	-8450	16.675
4	Mixture	11333.1	1.038	304.79	-2023	13.375
5	Mixture	11333.1	1.873	304.79	-2021	13.374
6	Mixture	11333.1	1.852	308.15	-1652	14.579
7	Recycled Whey	4991.4	1.038	308.15	2612	9.080
8	Treated Whey	6046.8	1.072	308.15	2612	9.080
9	Treated Whey	6046.8	1.013	300.58	2043	7.211
10	Biogas	272.7	1.038	308.15	-201964	203.721
100	Biogas	57.7	1.038	308.15	-201964	203.721
11	Biogas	57.7	1.163	318.37	-201585	203.984
12	Air	2315.4	1.013	298.15	-4713	199.130
13	Air	2315.4	4.331	900.00	13816	223.205
14	Gases	2373.1	1.066	542.44	-14710	217.957
15	Gases	4300.2	1.013	370.00	-47686	208.050
16	Steam	1697.1	10.013	453.10	50044	118.647
17	Condensate	1697.1	10.013	375.15	7714	23.938
18	Steam	66.8	4.013	416.89	49339	124.224
19	Condensate	66.8	1.088	375.15	7702	23.951
20	Hot Water	4985.0	2.513	343.15	5282	17.202
21	Hot Water	4985.0	1.013	335.78	4724	15.566
22	Steam	1566.6	10.013	453.10	50044	118.647
23	Condensate	1100.0	1.088	375.12	7700	23.946
24	Condensate	1697.1	1.088	375.12	7700	23.946
25	Steam	63.7	1.088	375.12	48262	132.075
26	Fresh Water	533.4	1.088	298.15	1889	6.611
27	Air	2315.4	4.558	497.37	1170	201.723
28	Gases	2373.1	4.114	1223.00	7904	231.928
29	Gases	2373.1	1.099	924.34	-2387	234.834
30	Biogas	215.0	1.038	308.15	-201964	203.721
31	Biogas	215.0	1.163	317.32	-201625	203.861
32	Air	1712.1	1.163	313.21	-4271	199.428
33	Air	1712.1	1.013	298.15	-4713	199.130
34	Gases	1927.1	1.066	1800.00	-29175	264.248

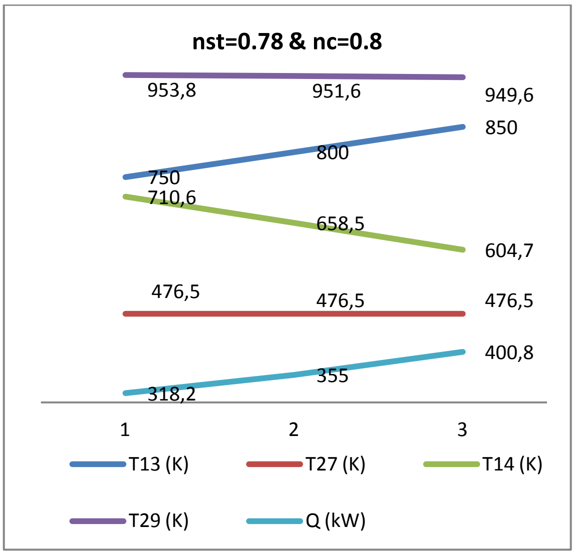
The electricity production is estimated around to 350 kW. Thus, the micro turbine single shaft model MT 350kW is selected to incorporate to the cheese whey anaerobic digestion treatment system. In order to match the selected micro turbine into the cheese whey anaerobic digestion system the technical data of this micro turbine as referred to the available literature should be applied in the model. However a parametric analysis (Figure 5-1) regarding the unknown value of the air temperature at the output of recuperator (T13 - 700 to 900 K) and the values of the turbine and air compressor efficiencies has been made.

In order to find the best value of these parameters the values resulted for the micro turbine electricity capacity and the temperatures of the MT Exhaust (T14), the air after compressor (T27) and the recuperator inlet temperature of the gases (T29) are examined in order to be as close as possible to those presented in [189].

The values of the other parameters which have been taking into account for the modeling of the system are presented in Table 5-6. The model also in this approach of the second scenario is developed through the method described in previous sections (Chapter 4).

Table 5-6 Micro turbine MT 350kW- Performance Parameters

Name	**Parameters**	**Values**
Compressor pressure ratio	P	4
Gases temperature of the MT combustion chamber (K)	T_{28}	1223.15
Pressure drop in CC (%)	dp	4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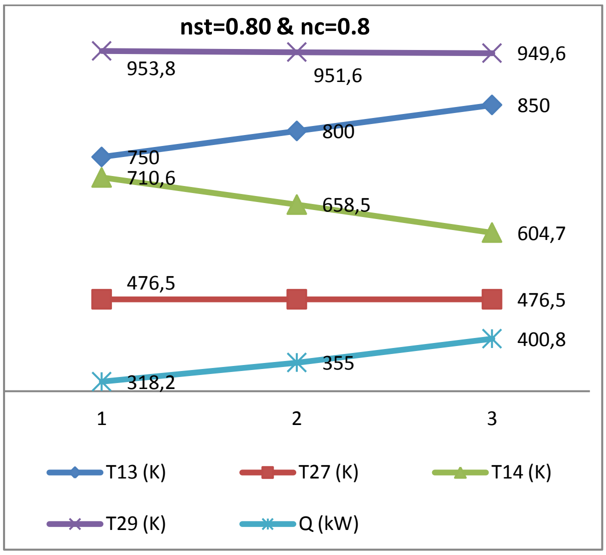
949,6
850
800
750
710,6
658,5
604,7
476,5
476,5
476,5
400,8
355
318,2
1
2
3
T13 (K)
T27 (K)
T14 (K)
T29 (K)
Q (kW)


nst=0.80 & nc=0.8
953,8
951,6
949,6
850
800
750
710,6
658,5
604,7
476,5
476,5
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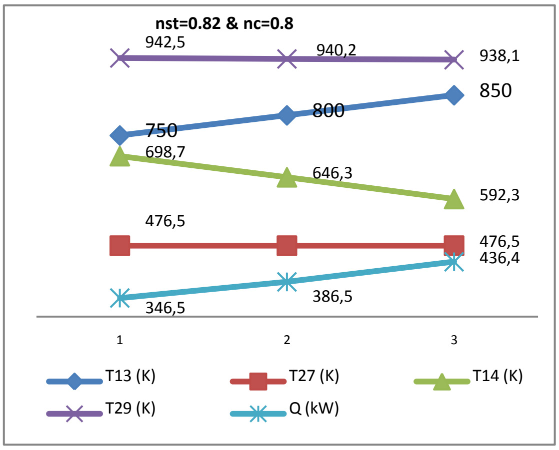
3
T13 (K)
T27 (K)
T14 (K)
T29 (K)
Q (kW)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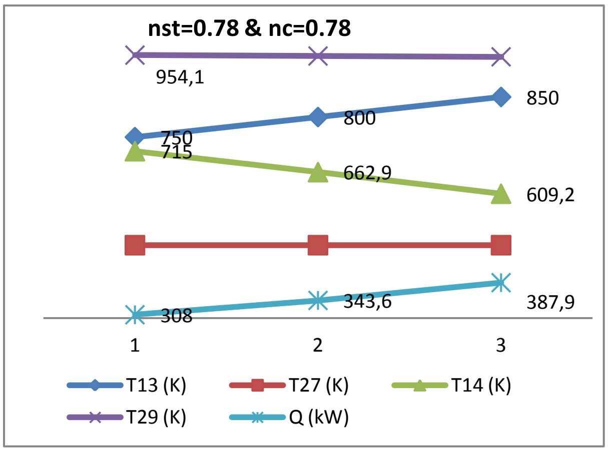
T29 (K)
Q (kW)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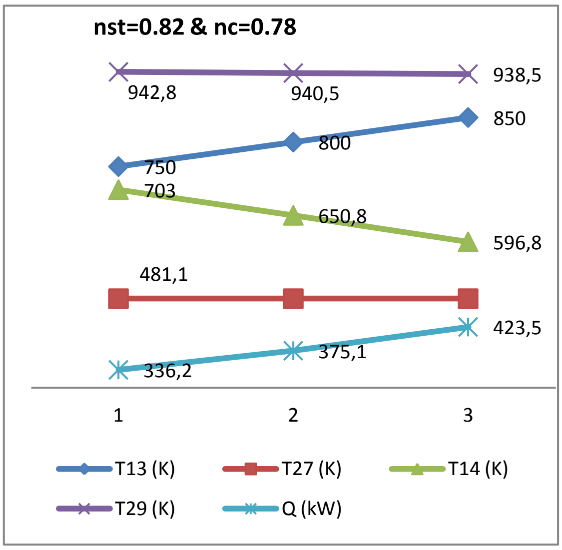
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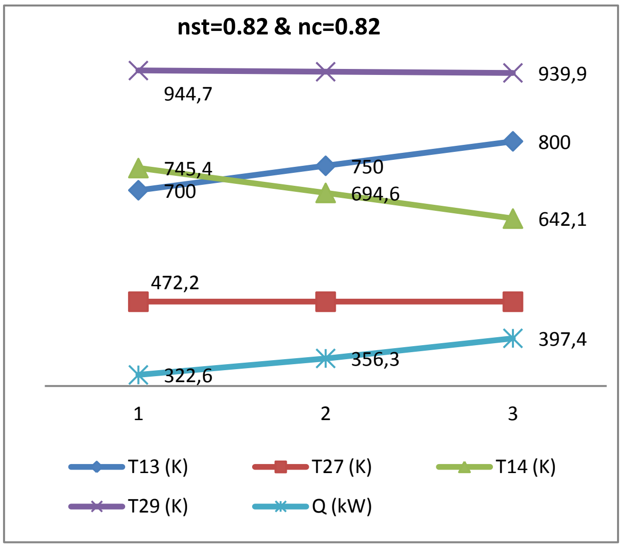
T14 (K)
T29 (K)
Q (kW)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Q (kW)

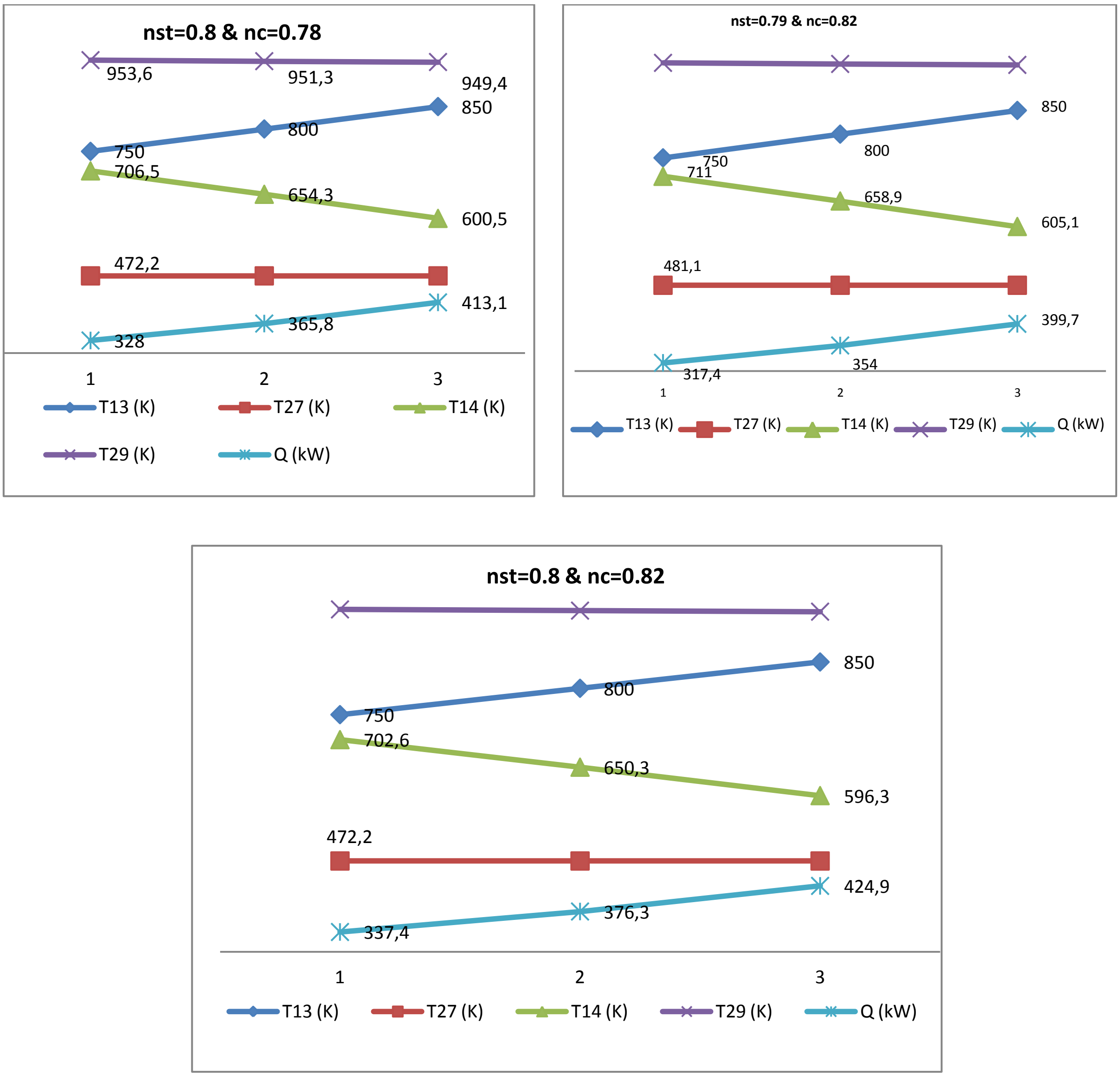

Figure 5-1 Parametric analysis for the air temperature at the output of recuperator (T13) and the isentropic efficiencies of compressor and turbine.

* The values of the axis x are referred to the number of run.

From the above graphs, it is obvious that the increase in the turbine isentropic efficiency value (n_{ST}) leads to an increase in the micro turbine electricity capacity and to a drop in the temperatures of the gases at the input (T29) and output (T14) of the recuperator without any influence on the compressed air temperature at the state 27, as it is expected. An increase in temperature of the compressed air at the output of the recuperator (T13) has as a result a decrease in the temperatures of T29 and T14 and an increase in the electricity capacity of the micro turbine without any other effect in the temperature of T27. Finally an increase in the compressor isentropic efficiency value ($n_{c)}$ as it is expected, leads to a reduction of the temperatures of T27, T14, T29 and to an increase in the micro turbine electricity capacity.

5.2.1 Model validation

Through the parametric analysis it has been decided that the most suitable values of the examined parameters of the air temperature at the output of recuperator is 800K and the values of the turbine and compressor efficiencies are 0.79 and 0.80 respectively. Following the model developed was validated with the data presented from the available literature [189] and the results are presented in Table 5-7.

Table 5-7 Validation of the model - scenario 2.

Name	Parameters	Manufacturer	Calculated
Electricity capacity (kW)	W_{MGT}	350	355
MT Exhaust Temperature (K)	T_{14}	589	658.52
Compressed air (K)	T_{27}	333.15	476.55
Recuperator inlet temperature	T_{29}	949.15	951.63

As it can be seen from Table 5-7, the model shows quite good agreement with the data from the literature although, there is a significantly difference to the compressed air temperature at state 27. This stemming from the fact that, the system is quite marginal in terms of biogas production and the technical characteristics of the anaerobic digestion treatment system which are based on realistic data, so the coupling is a quite difficult case.

The below Table 5-8 presents the thermodynamic properties of the new system as they have been resulted from the modeling of the system with the use of the selection micro turbine MT 350.

Table 5-8 Mass flow, pressure, temperature, enthalpy, entropy and fluid condition at each state of the system in scenario 2.

State	Fluid Condition	ṁ(kg/hr)	P(bar)	T(K)	h(kJ/kmol)	s(kJ/kmol)
1	Untreated Whey	6341.7	1.013	298.15	-8994	14.862
2	Untreated Whey	6341.7	1.569	298.15	-8992	14.862
3	Untreated Whey	6341.7	1.038	302.15	-8450	16.675
4	Mixture	11333.1	1.038	304.79	-2023	13.375
5	Mixture	11333.1	1.873	304.79	-2021	13.374
6	Mixture	11333.1	1.852	308.15	-1652	14.579
7	Recycled Whey	4991.4	1.038	308.15	2612	9.08
8	Treated Whey	6046.8	1.072	308.15	2612	9.08
9	Treated Whey	6046.8	1.013	300.58	2043	7.211
10	Biogas	272.7	1.038	308.15	-201964	203.721
100	Biogas	272.7	1.163	308.15	-201964	203.984
11	Biogas	272.7	1.163	318.37	-201585	199.13
12	Air	8096.8	1.013	298.15	-4713	220.16
13	Air	8096.8	3.849	800	13816	224.439
14	Gases	8369.5	1.066	658.52	-14710	209.498
15	Gases	8369.5	1.013	400	-47686	118.647
16	Steam	995.1	10.013	453.1	50044	23.938
17	Condensate	995.1	10.013	375.15	7714	124.224
18	Steam	66.8	4.013	416.89	49339	23.951
19	Condensate	66.8	1.088	375.15	7702	17.202
20	Hot Water	4985	2.513	343.15	5282	15.566
21	Hot Water	4985	1.013	335.78	4724	118.647
22	Steam	893	10.013	453.1	50044	23.946
23	Condensate	625.1	1.088	375.12	7700	23.946
24	Condensate	995.1	1.088	375.12	7700	132.075
25	Steam	35.3	1.088	375.12	48262	6.611
26	Fresh Water	334.7	1.088	298.15	1889	201.424
27	Air	8096.8	4.052	476.55	1170	233.572
28	Gases	8369.5	3.657	1223.15	7904	236.319
29	Gases	8369.5	1.099	951.63	-2387	234.834

Chapter 6 Exergy analysis

In this chapter an exergetic analysis of the model of the two different systems developed in Chapter 5 has been made. The target of this chapter is to evaluate the irreversibilities and thermodynamic inefficient after examining the exergetic performance and estimating the amount of exergy destruction and the efficiency of each system component.

6.1 Theoretical background

According to Bejan [190] the energy crisis of the '70s and the focusing on efficiency of fuel resources conservation has led to a complete overhaul of the way in which power systems are analyzed and improved thermodynamically. The exergy analysis and its optimization component (thermodynamic optimization or entropy generation minimization) constitute a new methodology which is based on simultaneous application of the first and second laws of thermodynamic in analysis and design (Figure 6-1). The exergy of the system is defined as the maximum theoretical work obtainable when the system interacts with the environment to reach equilibrium. This maximum theoretical work is obtained when all processes involved are reversible. According to Kotas [191]:

"*Exergy of a system is the amount of work obtainable when the system is brought to a state of unrestricted equilibrium (that is, thermal, mechanical and chemical) with the environment by means of reversible processes involving thermal and chemical interaction only with the environmen*t".

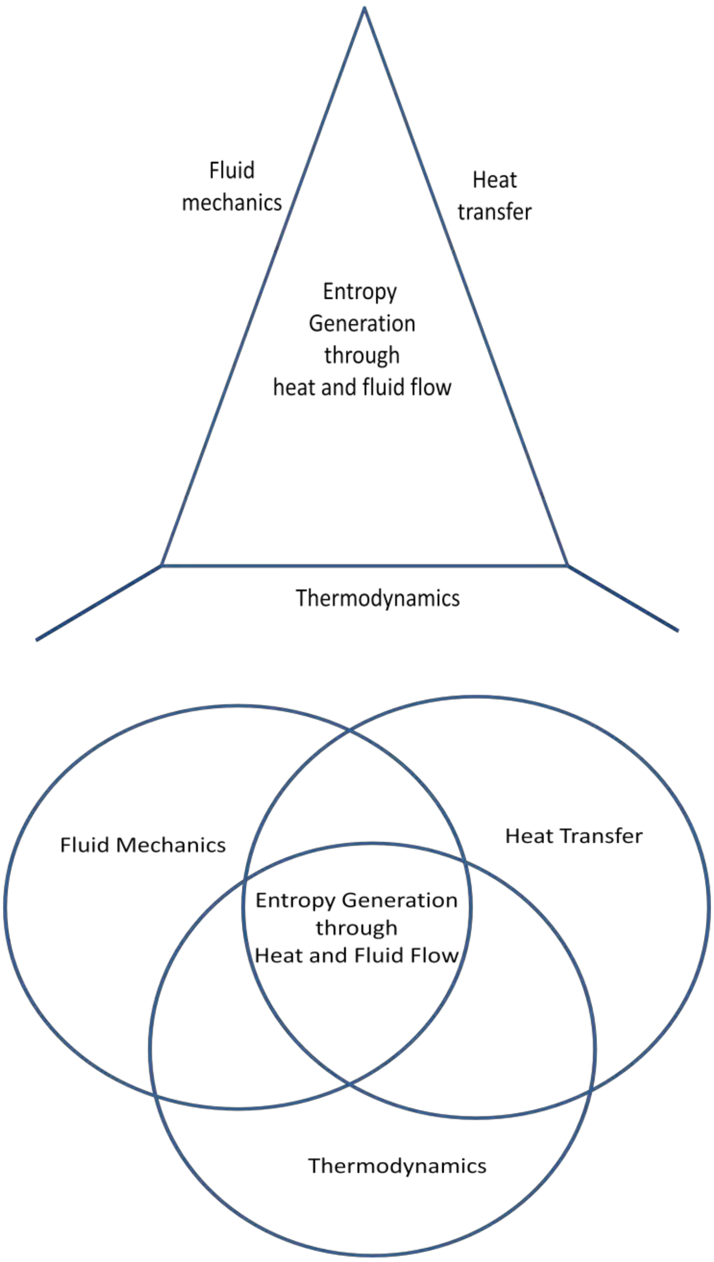

Figure 6-1 The interdisciplinary field covered by the method of thermodynamic optimization.

In all real processes some exergy will be destroyed (second law of thermodynamic). In an exergy analysis of a process, thermodynamic inefficiencies can be identified. Thus, the exergy analysis is able to detect the position, the type and the magnitude of irreversibilities losses on a thermal system [192, 193]. This information is useful either in designing or upgrading existing (energy) systems, since it can help to improve the performance by making the appropriate modifications leading to reduction of irreversibilities. There are three ways that the energy is transferred: with work, with heat and with mass flow. The exergy of a flow is the sum of four quantities:

$$e=e^{k} + e^{p} + e^{ph} + e^{ch} \tag{63}$$

Usually the components of the kinetic and potential exergy are considered negligible and are not taken into account.

The physical exergy at a given state is given from the following equation:

$$e^{PH} = \dot{m} * [(\bar{h} - \overline{h_0}) + P_0(\bar{s} - \bar{s_0}) \tag{64}$$

The chemical exergy of a gas mixture at a given state is defined as:

$$e^{CH} = \dot{m} * \sum x_k * \bar{e}_k^{CH} + R * T_0 * \sum x_k * \ln(x_k) \tag{65}$$

The overall exergy of a stream flow is calculated from the following relation:

$$\dot{E} = \dot{n}(e^{ph} + e^{ch}) \tag{66}$$

The exergy destruction rate in a control volume at steady state conditions can be calculated from the difference between the inlet and exit exergy flows.

$$\dot{E}_{des} = \sum_k (1 - \frac{T_o}{T_k}) \dot{Q}_k + \dot{W}_{cv} + \sum_k \dot{E}_k - \sum_e \dot{E}_e \tag{67}$$

The exergy balance and exergetic efficiencies for the basic components can be found in references [191, 194]. Apart from the burner and combustion chamber, all other components are treated as adiabatic. Table 6-1 concerns both of two scenarios which are described and analyzed in the previous chapter. The only difference relates to the second scenario where there are not the burner, air compressor 2 and biogas compressor 2.

For the <u>first scenario</u> examined:

The overall exergy balance of the system is written as:

$$\dot{E}_{des,sys} = \dot{E}_1 + \dot{E}_{12} + \dot{E}_{26} + \dot{E}_{23} + \dot{E}_{33} - \dot{E}_9 - \dot{E}_{15} - \dot{E}_{22} - (\dot{W}_{total,spent} + \dot{W}_{MT}) \quad (8)$$

The total exergetic efficiency is expressed through the above equation. It is the ratio of the net power output to the exergy supplied to the system.

$$e_{ex,sys} = \frac{\dot{E}_{22} - \dot{E}_{23} + \dot{W}_{MT}}{\dot{E}_1 + \dot{E}_{12} + \dot{E}_{33} + \dot{E}_{26} + \dot{W}_{total,spent}} \quad (9)$$

Similarly for the <u>second scenario</u> the above equations for the overall exergy balance and the total exergetic efficiency are converted as presented to the following relations:

Overall exergy balance:

$$\dot{E}_{des,sys} = \dot{E}_1 + \dot{E}_{12} + \dot{E}_{26} + \dot{E}_{23} - \dot{E}_9 - \dot{E}_{15} - \dot{E}_{22} - (\dot{W}_{total,spent} + \dot{W}_{MT}) \quad (70)$$

Total exergetic efficiency:

$$e_{ex,sys} = \frac{\dot{E}_{22} - \dot{E}_{23} + \dot{W}_{MT}}{\dot{E}_1 + \dot{E}_{12} + \dot{E}_{26} + \dot{W}_{total,spent}} \quad (71)$$

Table 6-1 Exergy destructions rates and exergy efficiencies

Pump 1	$\dot{E}_{des,p1}$	$-\dot{W}_{p1} + \dot{E}_1 - \dot{E}_2$
	$\dot{e}_{ex,p1}$	$(\dot{E}_2 - \dot{E}_1)/(-\dot{W}_{p1})$
Heat Exchanger 1	$\dot{E}_{des,HE1}$	$\dot{E}_2 + \dot{E}_8 - \dot{E}_3 - \dot{E}_9$
	$\dot{e}_{ex,HE1}$	$(\dot{E}_3 - \dot{E}_2)/(\dot{E}_8 - \dot{E}_9)$
Mixing unit	$\dot{E}_{des,MIX}$	$\dot{E}_3 + \dot{E}_7 - \dot{E}_4$
	$\dot{e}_{ex,mix}$	$(\dot{E}_4)/(\dot{E}_3 + \dot{E}_7)$
Pump 2	$\dot{E}_{des,p2}$	$-\dot{W}_{p2} + \dot{E}_4 - \dot{E}_5$
	$\dot{e}_{ex,p2}$	$(\dot{E}_5 - \dot{E}_4)/(-\dot{W}_{p2})$
Heat Exchanger 2	$\dot{E}_{des,HE2}$	$\dot{E}_5 + \dot{E}_{20} - \dot{E}_6 - \dot{E}_{21}$
	$\dot{e}_{ex,HE2}$	$(\dot{E}_6 - \dot{E}_5)/(\dot{E}_{20} - \dot{E}_{21})$
UASB reactor	$\dot{E}_{des,UASB}$	$\dot{E}_6 - \dot{E}_8 - \dot{E}_{10} - \dot{E}_7$
	$\dot{e}_{ex,UASB}$	$(\dot{E}_7 + \dot{E}_8 + \dot{E}_{10})/(\dot{E}_6)$
Biogas compressor	$\dot{E}_{des,comp1}$	$-\dot{W}_{comp1} + \dot{E}_{100} - \dot{E}_{11}$
	$\dot{e}_{ex,comp1}$	$(\dot{E}_{11} - \dot{E}_{100})/(-\dot{W}_{comp1})$
Air compressor 1	$\dot{E}_{des,comp2}$	$-\dot{W}_{comp2} + \dot{E}_{12} - \dot{E}_{27}$
	$\dot{e}_{ex,comp2}$	$(\dot{E}_{27} - \dot{E}_{12})/(-\dot{W}_{comp2})$
*Burner	$\dot{E}_{des,burner}$	$\dot{E}_{31} + \dot{E}_{32} - \dot{E}_{34}$
	$\dot{e}_{ex,burner}$	$(\dot{E}_{34})/(\dot{E}_{32} + \dot{E}_{31})$
Combustion Chamber	$\dot{E}_{des,CC}$	$\dot{E}_{11} + \dot{E}_{13} - \dot{E}_{28}$
	$\dot{e}_{ex,CC}$	$(\dot{E}_{28})/(\dot{E}_{11} + \dot{E}_{13})$
*Air compressor 2	$\dot{E}_{des,comp4}$	$-\dot{W}_{comp4} + \dot{E}_{33} - \dot{E}_{32}$
	$\dot{e}_{ex,comp4}$	$(\dot{E}_{32} - \dot{E}_{33})/(-\dot{W}_{comp4})$
Recuperator	$\dot{E}_{des,PH}$	$(\dot{E}_{29} + \dot{E}_{27} - \dot{E}_{13} - \dot{E}_{14}$
	$\dot{e}_{ex,PH}$	$(\dot{E}_{13} - \dot{E}_{27})/(\dot{E}_{29} - \dot{E}_{14})$
Turbine	$\dot{E}_{des,tur}$	$-\dot{W}_{tur} + \dot{E}_{28} - \dot{E}_{29}$
	$\dot{e}_{ex,tur}$	$-\dot{W}_{tur}/(\dot{E}_{29} - \dot{E}_{28})$
*Biogas compressor 2	$\dot{E}_{des,comp3}$	$-\dot{W}_{comp3} + \dot{E}_{30} - \dot{E}_{31}$
	$\dot{e}_{ex,comp3}$	$(\dot{E}_{31} - \dot{E}_{30})/(-\dot{W}_{comp3})$
Boiler	$\dot{E}_{des,boiler}$	$\dot{E}_{14} + \dot{E}_{34} + \dot{E}_{17} - \dot{E}_{15} - \dot{E}_{16}$
	$\dot{e}_{ex,boiler}$	$(\dot{E}_{16} - \dot{E}_{17})/(\dot{E}_{14} + \dot{E}_{34} - \dot{E}_{15})$
Steam Separator	$\dot{E}_{des,st\ sep}$	$\dot{E}_{16} - \dot{E}_{18} - \dot{E}_{22} - \dot{E}_{25}$
	$\dot{e}_{ex,st\ sep}$	$(\dot{E}_{18} + \dot{E}_{22} + \dot{E}_{25})/(\dot{E}_{16})$
Heat exchanger & Pump 3	$\dot{E}_{des,HE\ P3}$	$-\dot{W}_{P3} + \dot{E}_{18} + \dot{E}_{21} - \dot{E}_{19} - \dot{E}_{20}$
	$\dot{e}_{ex,HE\ P3}$	$(\dot{E}_{20} - \dot{E}_{21})/(-\dot{W}_{P3} + \dot{E}_{18} - \dot{E}_{19})$
Deaerator	$\dot{E}_{des,deaer}$	$\dot{E}_{19} + \dot{E}_{23} + \dot{E}_{25} + \dot{E}_{26} - \dot{E}_{24}$
	$\dot{e}_{ex,dearer}$	$(\dot{E}_{24})/(\dot{E}_{19} + \dot{E}_{23} + \dot{E}_{25} + \dot{E}_{26})$
Pump 4	$\dot{E}_{des,p4}$	$-\dot{W}_{p4} + \dot{E}_{24} - \dot{E}_{17}$
	$\dot{e}_{ex,p4}$	$(\dot{E}_{17} - \dot{E}_{24})/(-\dot{W}_{p4})$

*only for the first scenario studied.

6.2 Exergy analysis results for the first scenario

The analysis described in the previous paragraphs is applied to the developed model of the coupling micro turbine and cheese whey anaerobic digestion treatment plant in order to locate the main exergy destructions and identified inefficiencies. The exergy of each station of the system examined in this approach through the thermodynamic properties shown in the above Table 5-5 has been presented in the Table 6-2.

Figure 6-2 presents the exergy destruction rate of each component of the modeled system. It is obvious that the burner, the boiler and the combustion chamber contribute to the irreversibility of the system. This is due to the chemical reactions as well as the mixing processes taking places in these devices.

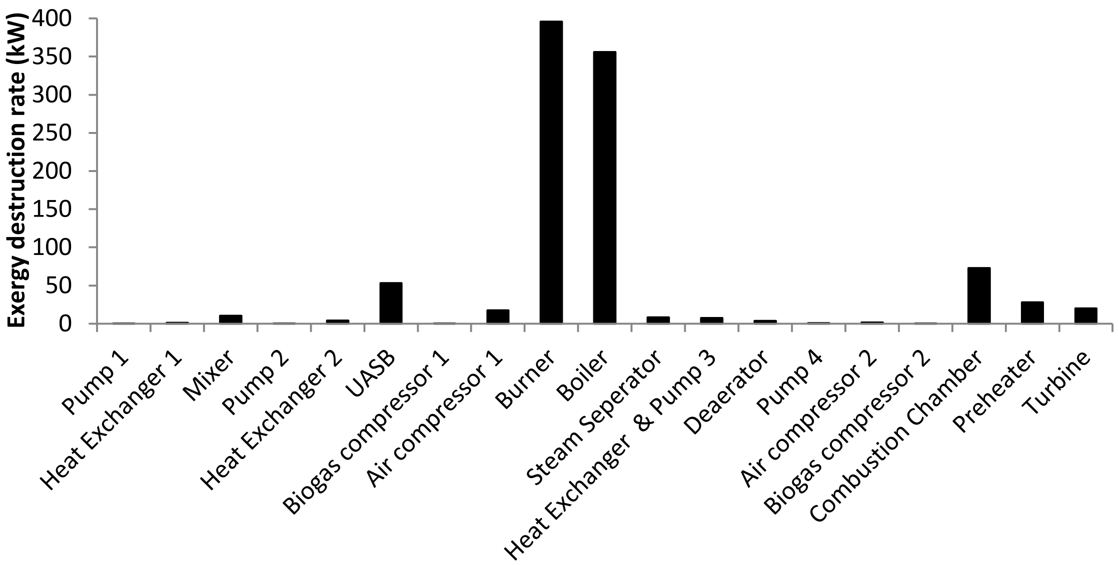

Figure 6-2 Exergy destruction rate of main devices at design point

Table 6-2 Exergy at each station – scenario 1

State	Fluid Condition	$\dot{E}$(kW)
1	Untreated Whey	1526.21
2	Untreated Whey	1526.30
3	Untreated Whey	1526.40
4	Mixture	1579.58
5	Mixture	1579.84
6	Mixture	1581.00
7	Recycled Whey	63.65
8	Treated Whey	77.11
9	Treated Whey	76.02
10	Biogas	1387.21
100	Biogas	293.48
11	Biogas	293.65
12	Air	0.03
13	Air	254.85
14	Gases	50.42
15	Gases	30.19
16	Steam	387.17
17	Condensate	18.42
18	Steam	12.80
19	Condensate	0.71
20	Hot Water	21.56
21	Hot Water	16.15
22	Steam	357.39
23	Condensate	11.66
24	Condensate	17.99
25	Steam	8.85
26	Fresh Water	0.37
27	Air	114.74
28	Gases	475.44
29	Gases	218.39
30	Biogas	1093.73
31	Biogas	1094.39
32	Air	5.96
33	Air	0.10
34	Gases	704.45

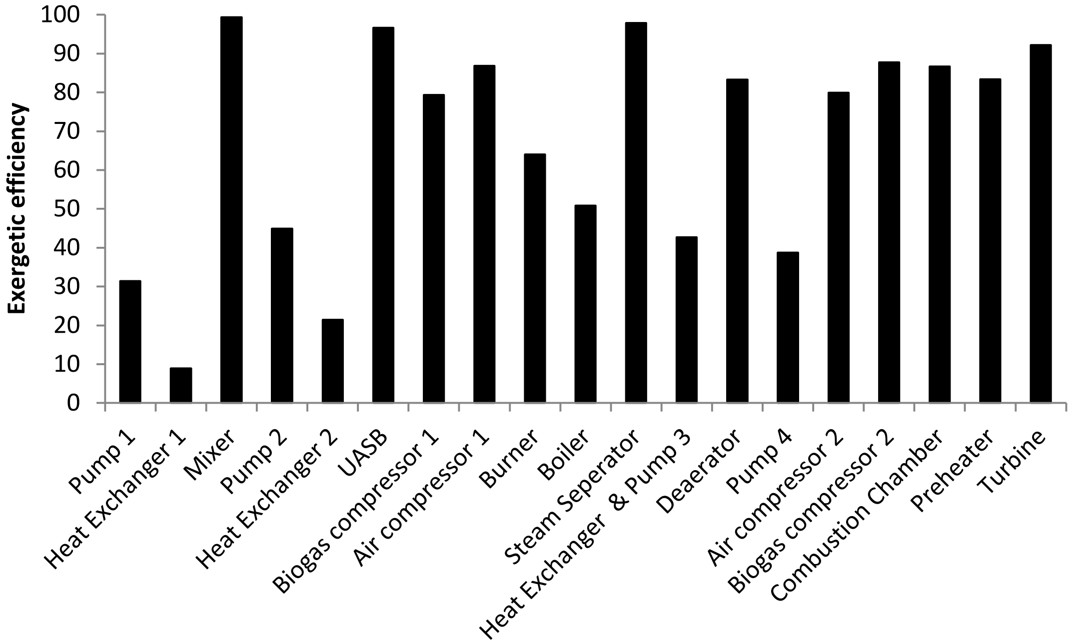

Figure 6-3 Exergetic efficiencies of main devices at design point – scenario 1

The exergetic efficiencies of the main components, i.e. the ratio of the exergy recovered to the supplied exergy, are presented in Figure 6-3. The lower exergetic efficiencies values are for the heat exchangers 1 & 2. This is due to the temperatures differences between the fluids and the pressure losses.

At this point, it is also should be mentioned that the introduction of the micro turbine system into the cheese whey anaerobic digestion treatment system has positive effects since the exergetic efficiency is now increased significantly (about of 30%) compared to the exergetic efficiency of the cheese whey anaerobic digestion system which has been calculated to 24% approximately.

This increase in exergetic efficiency is due to the reduction of the exergy losses in the boiler and the direct work production. The exergetic efficiency of the coupling system is quite high despite the high amount of the exergy losses. Figure 6-4 illustrates the exergy loss and the destruction balance for the whole system. There is a large amount of exergy loss to the burner and steam boiler which reaches to 76% of the total exergy destruction of the system.

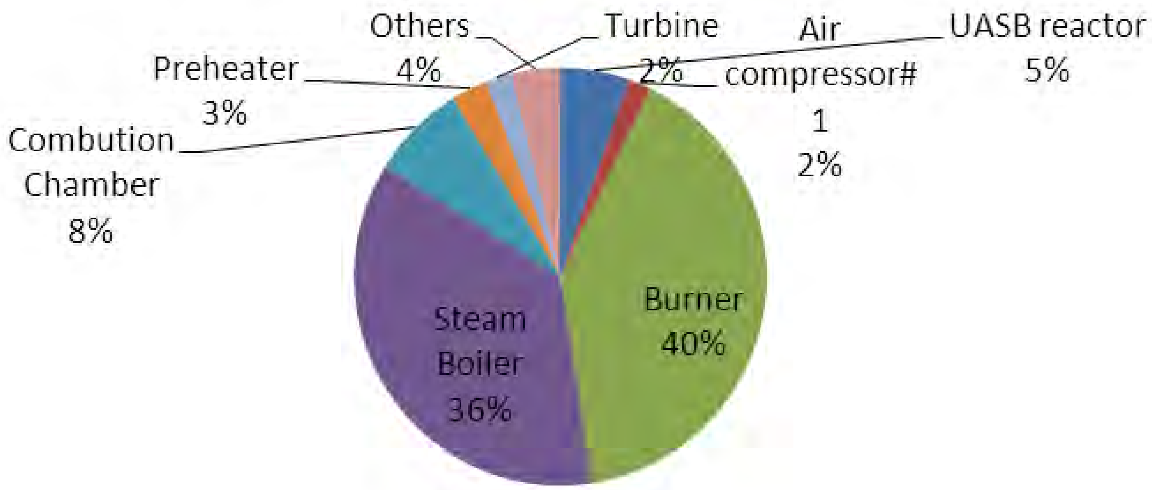

Figure 6-4 Exergy destruction in percentage of total exergy losses

6.3 Exergy analysis results for the second scenario

In this approach an exergetic analysis has been also carried out on the system modeled as has been presented in Chapter 5.2. For the exergetic analysis the relations presented in Chapter 6.1 have been used. The exergy of each flow is calculated at all states and the changes in exergy are determined for each major component. The exergy destruction rate and exergetic efficiencies are also calculated for each state according to the relations presented in Table 6-1 above.

The exergy of each station of the system examined in this scenario through the thermodynamic properties shown in the above Table 5-5 has been presented in the Table 6-3.

The exergy analysis results are summarized in Figure 6-5 and show that the highest exergy destruction occurs in the combustion chamber, mainly due to the irreversibilities associated with combustion and the larger temperature difference between the air entering the combustion chamber and the flame temperature. The recuperator exhibits the next largest exergy destruction, mainly due to the temperature difference between two fluid streams passing through it, but also due to the pressure drop across the device.

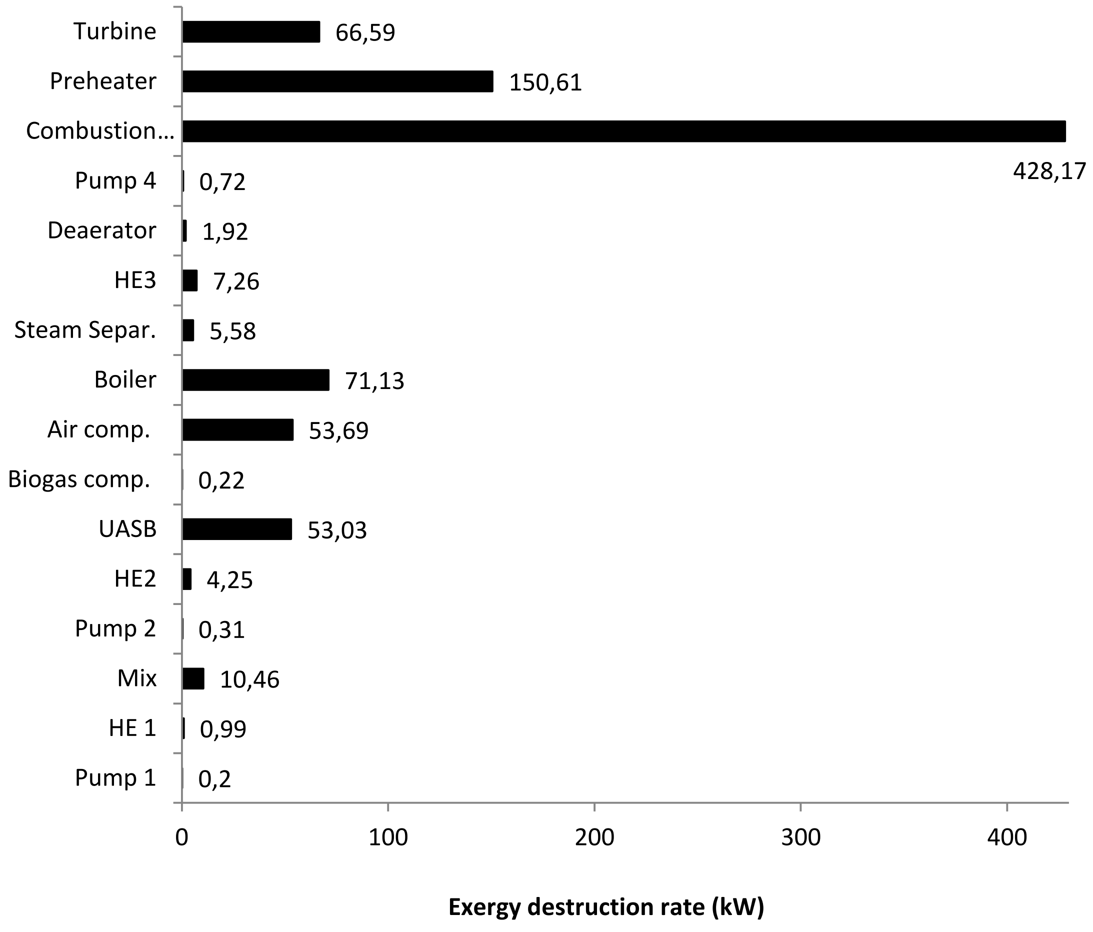

Figure 6-5 Exergy destruction rate of main devices at design point (Scenario 2)

Table 6-3 Exergy at each station – scenario 2

State	**Fluid Condition**	**$\dot{E}$(kW)**
1	Untreated Whey	1526.21
2	Untreated Whey	1526.30
3	Untreated Whey	1526.40
4	Mixture	1579.58
5	Mixture	1579.84
6	Mixture	1581.00
7	Recycled Whey	63.65
8	Treated Whey	77.11
9	Treated Whey	76.02
10	Biogas	1387.21
100	Biogas	1387.21
11	Biogas	1388.04
12	Air	0.67
13	Air	706.85
14	Gases	333.35
15	Gases	46.01
16	Steam	227.02
17	Condensate	10.80
18	Steam	12.80
19	Condensate	0.71
20	Hot Water	21.56
21	Hot Water	16.15
22	Steam	203.73
23	Condensate	6.63
24	Condensate	10.55
25	Steam	4.90
26	Fresh Water	0.23
27	Air	358.62
28	Gases	1666.73
29	Gases	832.20

Figure 6-6 shows for each component the dimensionless exergy destruction ratio. This measure is useful for prioritizing exergy losses in an intuitive manner. Both exergy destruction and the dimensionless exergy destruction ratio are higher in the combustion chamber than in the other components, suggesting that it would be worthwhile to focus improvement efforts on this component.

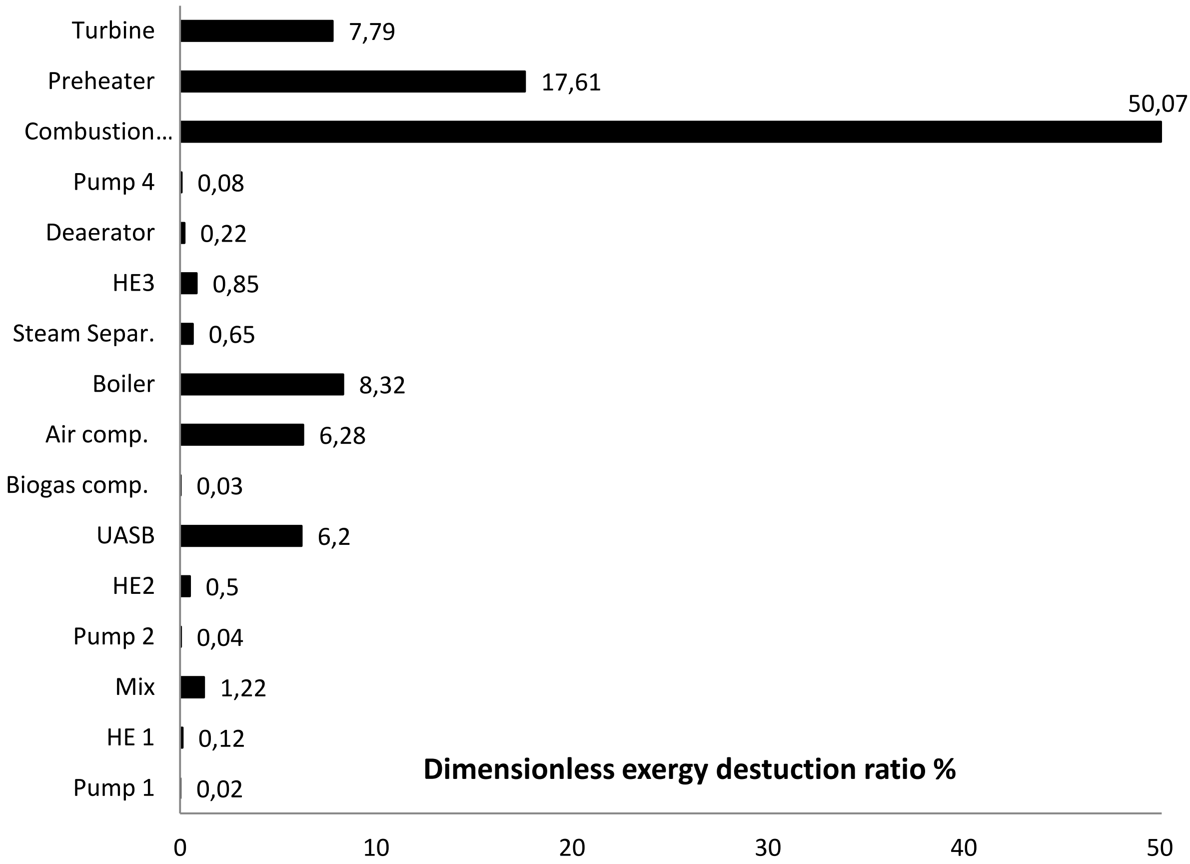

Figure 6-6 Dimensionless exergy destruction ratio for the components of the whole CHP modeled system – scenario 2

The exergetic efficiencies of the main components, i.e. the ratio of the exergy recovered to the supplied exergy, are presented in Figure 6-7. Also in this approach, the lower exergetic efficiencies values are for the heat exchangers 1 & 2. This is due to temperatures differences between the fluids and the pressure losses.

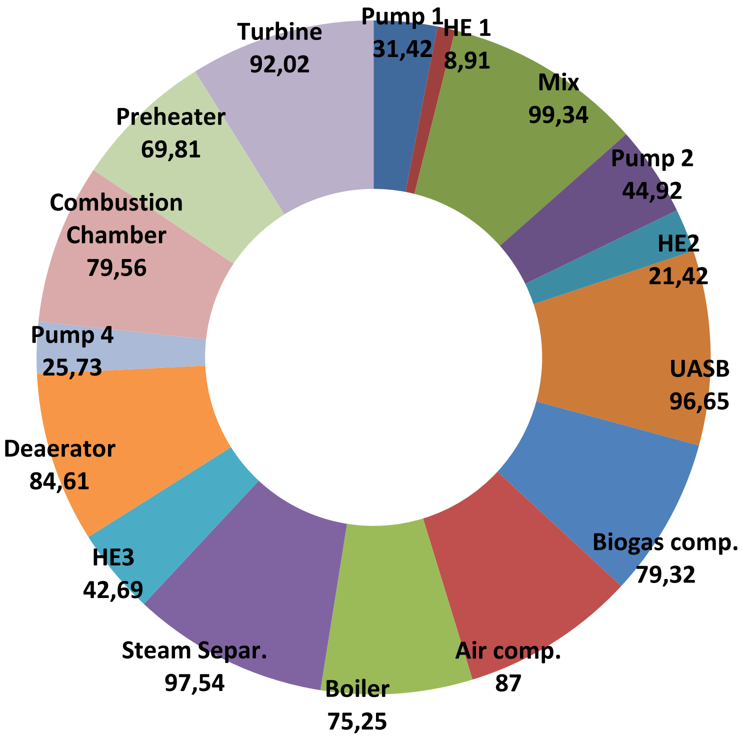

Figure 6-7 Exergetic efficiencies of main devices at design point – scenario 2

The total exergy efficiency of the system examined in this scenario 2, is increased significantly compared to the model developed in scenario 1 and the initially system without the incorporation of micro turbine and reaches to 36.26%, as expected using the micro turbine with higher electricity capacity.

6.4 Conclusions of the exergy analysis of both scenarios examined

From the previous results of the exergy analysis of the two scenarios examined it is obvious that the two micro turbines (T100 and MT350) selected for both case studies examined can be combined effectively with the cheese whey anaerobic digestion treatment plant. Furthermore, in order to obtain a clearer picture about the exergetic effectiveness of the systems examined in both cases; it has been decided to compare these systems with the initially cheese whey anaerobic digestion system without micro turbine using. For this target the above graph (Figure 6-8) has been made.

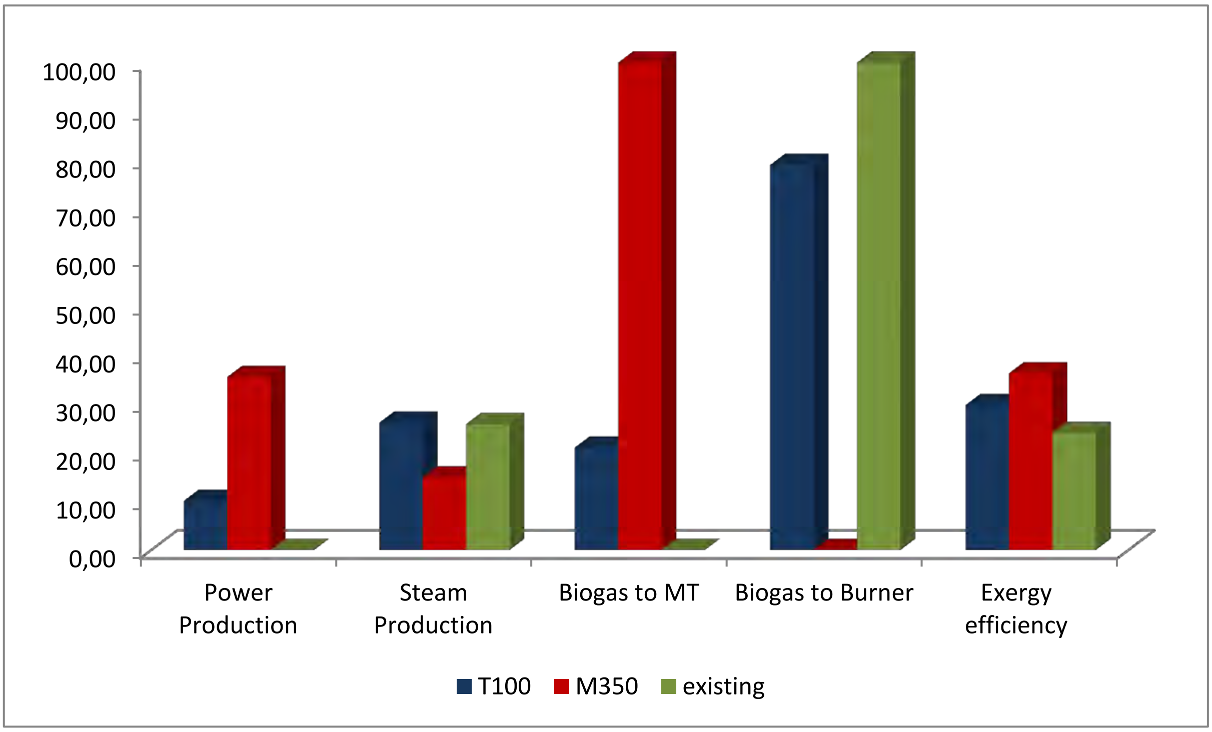

Figure 6-8 Results from the exergetic analysis*

* The power production (kW) is divided by 10, the steam production is in kg/min, the biogas to MT and to burner is a percentage of the total biogas amount (%), the exergy efficiency (%).

As it has been discussed in the previous sections of exergy analysis in the first scenario examined, only a part of the biogas produced through Anaerobic Digestion of cheese whey is guided to the micro turbine while the rest part is used for steam production in order to cover the industry heat requirements. From Figure 6-8 it is obvious that in this case the steam production is quite higher and the electricity production is quite lower comparing to the second scenario examined in which the whole biogas produced is used for energy production.

The Anaerobic Digestion system coupled with the micro turbine T350 operates efficiently and could produce peak energy production with simultaneous noticeable steam production.

Moreover from this graph, it is obvious that the exergetic efficiency of the system of the second scenario examined is increased significantly compared with the initially system without micro turbine, as it is expected. Thus, the bigger (between the two consider) the micro turbine coupled with the cheese whey Anaerobic Digestion plant, the more exergetic efficient is the corresponding system obtained, while the smaller size of the micro turbine contributed to lower values of total power output.

Through exergetic analysis, it is concluded that the micro turbines is an attractive solution to be coupled with Anaerobic Digestion systems in order to obtain electricity production. The choice of the engine depends on the installation requirements, as it has been discussed in the previous chapter 5.

Moreover, by the analysis described in the previous sections of this chapter which is applied to the developed systems of two scenarios examined the main exergy destructions are located. At this point Figure 6-9 has been made in order to present the overall exergy destruction rate of each component of the systems examined both in two scenarios along with this of the initially anaerobic digestion system without micro turbine using.

It is obvious that for the system without micro turbine using and for the system coupled with micro turbine T100, the burner contribute the most significant exergy destructor. This is due to the chemical reactions and the large temperature difference between the burner and working fluid as well as the mixing processes taking places in the burner, are the main source of irreversibility. Additionally the high differences between the fluids which are occurred in the boiler they are constituted another important reason for irreversibilities in both of these systems.

Regarding the system obtained from the second scenario, the micro turbine's combustion chamber contributes the most to the irreversibility. This is also due to the chemical reactions, the large temperature differences and mixing processes taking places in this device.

Taking into account the previous results, certain improvements may be suggested in order to reduce the system exergy destruction. A possible improvement refers to the utilization of the exhaust gas heat carrying an exergy amount which can be used further for energy production. A heat recovery steam generator or/and an absorption chiller may could be used for this reason. Another improvement would be the operation at higher fuel utilization factor as it results in reduced irreversibilities at the system and fuel utilization factor will be regulated simultaneously in order to achieve the optimal performance. Finally, as large amounts of exergy are destructed in the boiler, an optimization concerning the matching of the temperature levels on this device could probably reduce irreversibilities

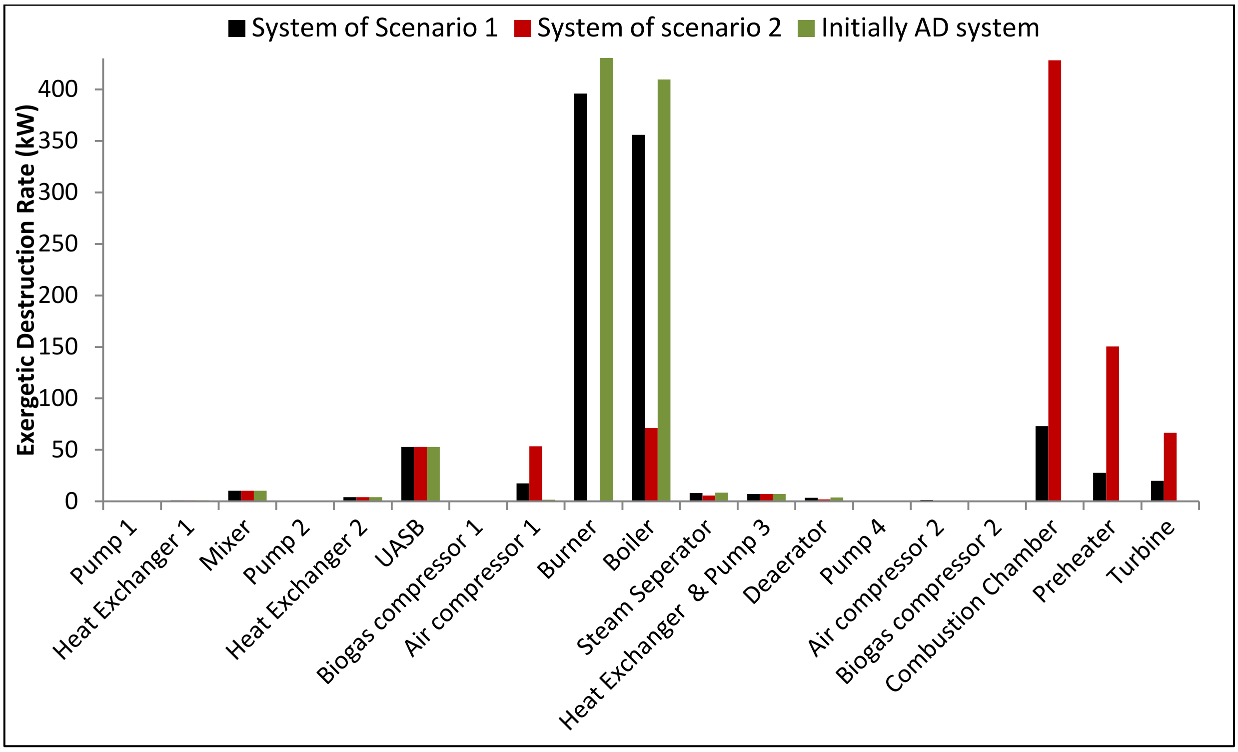

Figure 6-9 Exergetic Destructions for each scenario examined

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Chapter 7 Economic analysis

From the previous sections, it was established that the system modeled is an exergetic efficient system. However, the exergetic efficiency alone does not give much justification to approve whether a system is worth execution or not. Hence, to fully establish whether the system is worth execution, it is customary to evaluate also its economic viability through economic analysis. In this chapter the economic analysis of the system model developed in previous sections in both of two scenarios is performed using the method of Net Present Value (NPV) [11]. Thus, the economic analysis of the system described in the present chapter includes purchased equipment cost (PEC) of all the components, installation cost, material cost etc and operation & maintenance (O&M) costs.

7.1 Theoretical background

There are many profitability assessments methods in the available literature to evaluate investments [195]. Among others the NPV method is one of the most common method in investment evaluation [196]. Alkaraan and Northcott (2006) [197] have analyzed the use of conventional investment appraisal techniques such as payback period, return on assets, return on investment, internal rate of return, NPV and risk analysis approaches such as parametric analysis, adjustment of the payback period, or discount rate.

The Net Present Value was used as an evaluation criterion. This value calculates all incomes and outgoings in the economic life of the project [195]. The net present value can be either positive or negative. A positive NPV presents a net gain corresponding to the cash flow, while a negative present value indicates a net loss. Projects with negative NPV are usually rejected, while those with the highest NPV among various alternatives are always given the highest preference.

The NPV is calculated as the difference of the net cash flows minus the investment capital and is given by the relation:

$$\mathrm{NPV} = \sum \frac{\mathrm{NCF}}{(1+\mathrm{i})^{\mathrm{t}}} - \mathrm{TCI} \tag{72}$$

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

TCI or Total Capital Investment constitutes the total cost of the system presented in previous sections in both scenarios 1 & 2. The costs have been considered in the analysis are the following and presented in detailed in Table 7-1 below:

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

In this study has been considered that the incoming cash flows come from the saving in natural gas and from the selling of the generated electricity to the national grid.

Natural gas, usually, is the fuel used by industries to cover their thermal needs. So the same amount of steam produced by biogas would have to be produced by natural gas.

7.2 Parametric values and assumptions for the economic analysis of the modeled system

In order, to carry out the economic analysis the following parameters and costs are taken into account [11]:

1. The anaerobic digestion system for the cheese whey treatment has been on operation since 2009.
2. The installation of the micro turbine in the anaerobic digestion system has been made 4 years later on 2013.
3. The operation of the anaerobic treatment is 270 days per year or 6480 h per year.
4. The maintenance cost of the GT is assumed to increase annually by 3%.
5. The present value of the sold electricity to the network is 0.253 €/kWh and it is assumed invariant according to Government Gazette 85/A/04.06.2010.
6. The annual increase rate of the consumable cost (such as soda which is used for the pH regulation into the reactor) is 3%.
7. 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%.

8. The maintenance cost is divided into the below categories:

   - Pumps and Compressors maintenance cost which is assumed to be equal to 4% of the purchase cost
   - Measuring, sampling and electronic devices maintenance cost which refers to the devices used in the subsystem extends up to the biogas compressor without the buffer tank which is assumed to be equal to 2% of the purchase cost
   - Rest of the equipment maintenance cost, such as the reactor, the steam boiler, the deaerator, the mixing and separation unit, the heat exchangers, the piping and the valves which is assumed to be equal to 5% of the purchase cost.

     The increase in maintenance cost is 3% per year.
   - Micro turbine maintenance cost which refers to the devices of the micro turbine system such as the turbine, compressor, recuperator etc.

For the cost calculation the system modeled has been divided into three subsystems. The reason is that the system was executed by more than one supplier who had different cost accounting policies. The costs of three subsystems are presented in the Tables 7-1 to 7-3. Two of these subsystems (Table 7-1 and 7-2) are common for the two examined scenarios.

The cost of the third subsystem is varied for the two scenarios examined due to the different type of the micro turbine used.

1. **1st Subsystem:** extends up to the biogas compressor without the buffer tanks. The costs of each component are presented in the above table (Table 7-1).

Table 7-1 Data for the equipment cost of Subsystem 1 [13]

	Components	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 reactor	440,000
	Biogas compressor	80,000
	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 Subsytem 1	**1,000,000**

2. **2nd Subsystem**: starts from the air compressor and goes up to the steam delivery to the plant. The costs of each component are presented in the above table (Table 7-2).

Table 7-2 Data for the equipment cost of Subsystem 2 [13]

	Components	Cost (€)
Subsystem 2	Air compressor	5,000
	Burner	55,000
	Steam boiler	150,000
	Steam Separator	2,000
	Heat Exchanger 3 and Pump 3	5,000
	Deaerator	60,000
	Pump 4	3,000
	Buffer tanks for whey	120,000
	Piping, valves, racks	165,000
	Cost of equipment (PEC) of Subsystem 2	565,000
	Installation cost (~45% of PEC)	254,000
	TCI of Subsytem 2	**819,000**

The civil cost for two subsystems is equal to 250,000 €, so the total TCI of the subsystems 1 &2 is equal to 2,069,000 €.

3. **3rd Subsystem**: this subsystem refers to the micro turbine systems which have been selected in the two examined scenarios presented in the previous chapters. In the following table (Table 7-3) the costs of the various micro turbines systems are presented.

Table 7-3 Data for the micro turbine cost

Estimated Capital Cost for MGT [198]					
Micro turbine	C30(1)	C65(1)	MT250(2)	T100(3)	MT350(4)
Nominal Capacity (kW)	30	65	250	100	350
Equipment					
Gen Set Package(€)	981	980	1,081		
Heat Recovery and other equipment (€)	330	260	146		
Total equipment (€)	1,311	1,240	1,226		
Labor/Materials (€)	544	276	269		
Total Process Capital (€)	1,855	1,516	1,495	1508	1233
Project and Construction Management(€)	161	153	146	145.20 *	145.88
Engineering and fees(€)	161	153	146	145.20*	145.88
Project Contingency(€)	69	62	61	61.20*	61.40
Project Financing (interest during construction) (€)	23	23	23	23.20 *	23
Total Plant Cost €/KW	2,269	1,907	1,871	1,882.80	1,609.16
kWh/year				648000	2,268,000
O/M Costs - Service Contract, €/KWh	0.012-0.020	0.011-0.017	0.010-0.018	0.016	0.022
Total Cost (€)				**188,280**	**563,206**

*Values which have been evaluated approximately based on the other MGT values of the Table due to their unavailability in the literature. (1) Capstone Turbine Corp manufacturer, (2) Ingersoll Rand manufacturer, (3) Turbec manufacturer, (4)referred in EPA [199]. The values obtain after conversion of dollars to euros (1 dollar=0.766 euros).

For the economic analysis it has been assumed that the company has been taken a first loan from a bank in 2009 for the Subsystems 1&2 investment costs in 2009 and a second loan from the same bank in 2013 for the investment cost of Subsystem 3. For both of these two loans the interest rate is 7%.

The annual amount of the installment can be calculated by the following relation:

$$AD = \frac{\varepsilon\,(1+\varepsilon)^{\nu}}{(1+\varepsilon)^{\nu}-1}\,K \tag{73}$$

Moreover, it has been considered that the first loan will be paid back in ten years and the second one in seven years in order the company pay back together the two loans in the year of 2020. The installments will be constant over these years.

As already stated above the incoming cash flow comes from the saving in natural gas for the first year (2009) amounts to 317,829 €. The mean cost of natural gas in 2009 was 0.31879 €/m^3 and it was assumed to increase annually by 7%. It is assumed that the company purchases the electricity from the national grid in order to cover its thermal needs in lower price (0.08 €/kWh) and sells the generated electricity through micro turbine to the national grid at a higher price as it has been referred previously (0.253 €/kW). Moreover, the discount rate or rate of return is assumed to be 5%.

7.3 Economic analysis of scenario 1

From the individual profitability assessment method of NPV and the parameters and data presented above, the economic analysis of the system described in the first scenario is carried out. As it has been refereed, the examined system is a coupling system of the cheese whey anaerobic digestion system and the micro turbine T100. The results of the economic analysis are presented in Table 7-4. It is shown that the total NPV of the system in this approach reaches to 1,767,434 €. The cash flow and the incomings resulting through the economic analysis of the system are illustrated in the below diagram (Figure 7-1).

The incomings are calculated as the sum of the incomings of natural gas and the incomings of the selling of the micro turbine’s electricity generation to the national grid for each year. The cash flows for each year constitute a result of the difference between the incomings minus the maintenance and the operation costs.

Table 7-4 Incoming and outgoing flows and NPV calculation (in Euros) for the system examined in scenario1.

			Operational Costs		Maintenance Costs										
Year	**Cal. Year**	**Labor cost**	**Consumables**	**Electricity**	**Pumps-Compressors**	**Instruments**	**Other**	**MT**	**Installments for MT**	Installments	Incoming cash flow from natural gas	Incoming cash flow from electricity	Incomings for extended system	Cash flow - extended System	Cash flow based on Present Value
0	2009													-2,257,280	-2,257,280
1	2010	70,000	53,000	5,614	6,320	1,000	4,610			294,615	317,829		317,829	-117,330	-111,743
2	2011	72,100	54,590	6,007	6,510	1,030	4,748			294,615	340,077		340,077	-99,523	-90,270
3	2012	74,263	56,228	6,427	6,705	1,061	4,891			294,615	363,882		363,882	-80,307	-69,372
4	2013	76,491	57,915	6,877	6,906	1,093	5,037	10,368	34,936	294,615	389,354	163,944	553,298	59,060	48,589
5	2014	78,786	59,652	7,359	7,113	1,126	5,189	10,679	34,936	294,615	416,609	163,944	580,553	81,099	63,543
6	2015	81,149	61,442	7,874	7,327	1,159	5,344	10,999	34,936	294,615	445,772	163,944	609,716	104,870	78,256
7	2016	83,584	63,285	8,425	7,546	1,194	5,505	11,329	34,936	294,615	476,976	163,944	640,920	130,501	92,744
8	2017	86,091	65,183	9,015	7,773	1,230	5,670	11,669	34,936	294,615	510,364	163,944	674,308	158,126	107,026
9	2018	88,674	67,139	9,646	8,006	1,267	5,840	12,019	34,936	294,615	546,089	163,944	710,033	187,892	121,117
10	2019	91,334	69,153	10,321	8,246	1,305	6,015	12,380	34,936	294,615	584,316	163,944	748,260	219,955	135,033
11	2020	94,074	71,228	11,044	8,494	1,344	6,195	12,751			625,218	163,944	789,162	584,032	341,472
12	2021	96,896	73,364	11,817	8,748	1,384	6,381	13,134			668,983	163,944	832,927	621,202	345,908
13	2022	99,803	75,565	12,644	9,011	1,426	6,573	13,528			715,812	163,944	879,756	661,206	350,652
14	2023	102,797	77,832	13,529	9,281	1,469	6,770	13,934			765,919	163,944	929,863	704,251	355,694
15	2024	105,881	80,167	14,476	9,560	1,513	6,973	14,352			819,533	163,944	983,477	750,556	361,030
16	2025	109,058	82,572	15,489	9,846	1,558	7,182	14,782			876,900	163,944	1,040,844	800,356	366,652
17	2026	112,329	85,049	16,573	10,142	1,605	7,398	15,226			938,283	163,944	1,102,227	853,905	372,556
18	2027	115,699	87,601	17,734	10,446	1,653	7,620	15,683			1,003,963	163,944	1,167,907	911,472	378,736
19	2028	119,170	90,229	18,975	10,759	1,702	7,848	16,153			1,074,240	163,944	1,238,184	973,347	385,187
20	2029	122,745	92,936	20,303	11,082	1,754	8,084	16,638			1,149,437	163,944	1,313,381	1,039,840	391,905
														NPV	**1,767,434**

Through the graph below it can be easily understood that both of the incomings and cash flows increase considerably every year. As it is expected a significant increase of the cash flow is presented in the year of 2020 when the company will have pay back the two loans. Moreover, in the incomings a significant increase occurs in the year of 2013 when the micro turbine is incorporated to the system of the cheese whey anaerobic digestion treatment.

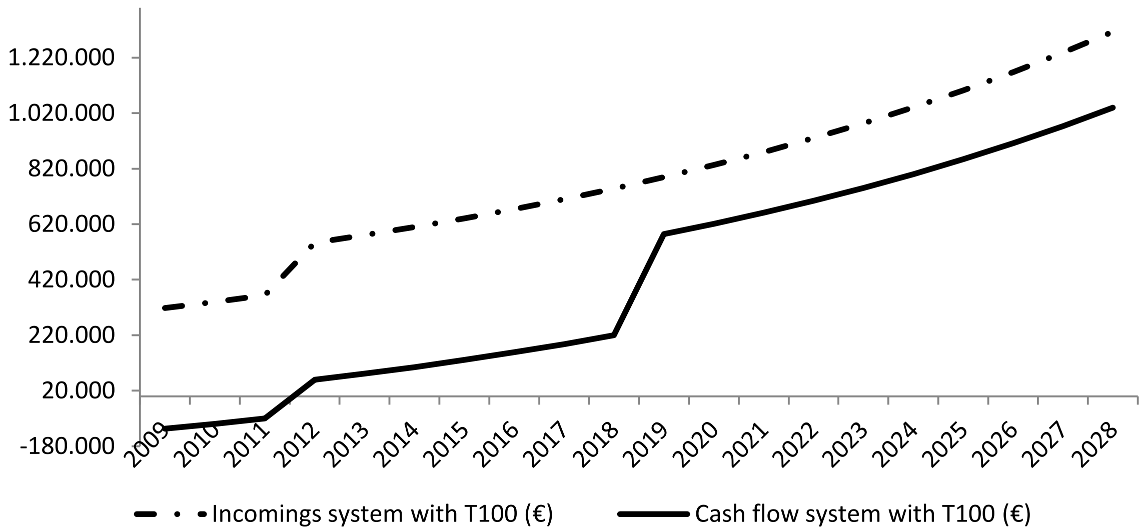

Figure 7-1 Incomings and cash flows diagram for the system in scenario 1

7.4 Economic analysis of scenario 2

In this case the total cost is constituted by the coupling system of the cheese whey anaerobic digestion treatment system and the micro turbine T350, as it has been selected in previous Chapter. The method of NPV as presented above has been used. The results from the economic analysis of this case are presented in the below table (Table 7-5).

Table 7-5 Incoming and outgoing flows and NPV calculation (in Euros) for the system examined in scenario 2.

		Operational Costs			Maintenance Costs										
Year	Cal. Year	Labor cost	Consumables	Electricity	Pumps-Compressors	Instruments	Other	MT	Installments for MT	Installments	Incoming cash flow from natural gas	Incoming cash flow from electricity	Incomings for extended system	Cash flow - extended System	Cash flow based on Present Value
0	2009													-2.632.206	-2.632.206
1	2010	70.000	53.000	1.767	6.320	1.000	4.610			294.615	317.829		317.829	-113.483	-108.079
2	2011	72.100	54.590	1.891	6.510	1.030	4.748			294.615	340.077		340.077	-95.407	-86.537
3	2012	74.263	56.228	2.023	6.705	1.061	4.891			294.615	363.882		363.882	-75.903	-65.568
4	2013	76.491	57.915	2.165	6.906	1.093	5.037	36.288	104.505	294.615	389.354	573.804	963.158	378.144	311.100
5	2014	78.786	59.652	2.316	7.113	1.126	5.189	37.377	104.505	294.615	416.609	573.804	990.413	399.736	313.203
6	2015	81.149	61.442	2.478	7.327	1.159	5.344	38.498	104.505	294.615	445.772	573.804	1.019.576	423.059	315.693
7	2016	83.584	63.285	2.652	7.546	1.194	5.505	39.653	104.505	294.615	476.976	573.804	1.050.780	448.242	318.557
8	2017	86.091	65.183	2.837	7.773	1.230	5.670	40.842	104.505	294.615	510.364	573.804	1.084.168	475.421	321.784
9	2018	88.674	67.139	3.036	8.006	1.267	5.840	42.068	104.505	294.615	546.089	573.804	1.119.893	504.745	325.363
10	2019	91.334	69.153	3.249	8.246	1.305	6.015	43.330	104.505	294.615	584.316	573.804	1.158.120	536.369	329.284
11	2020	94.074	71.228	3.476	8.494	1.344	6.195	44.630			625.218	573.804	1.199.022	969.581	566.894
12	2021	96.896	73.364	3.719	8.748	1.384	6.381	45.969			668.983	573.804	1.242.787	1.006.324	560.359
13	2022	99.803	75.565	3.980	9.011	1.426	6.573	47.348			715.812	573.804	1.289.616	1.045.911	554.669
14	2023	102.797	77.832	4.258	9.281	1.469	6.770	48.768			765.919	573.804	1.339.723	1.088.547	549.790
15	2024	105.881	80.167	4.556	9.560	1.513	6.973	50.231			819.533	573.804	1.393.337	1.134.456	545.693
16	2025	109.058	82.572	4.875	9.846	1.558	7.182	51.738			876.900	573.804	1.450.704	1.183.874	542.347
17	2026	112.329	85.049	5.216	10.142	1.605	7.398	53.290			938.283	573.804	1.512.087	1.237.058	539.724
18	2027	115.699	87.601	5.582	10.446	1.653	7.620	54.889			1.003.963	573.804	1.577.767	1.294.278	537.799
19	2028	119.170	90.229	5.972	10.759	1.702	7.848	56.536			1.074.240	573.804	1.648.044	1.355.827	536.547
20	2029	122.745	92.936	6.390	11.082	1.754	8.084	58.232			1.149.437	573.804	1.723.241	1.422.019	535.944
														NPV	4.812.361

As it can be seen from Table 7-5 the total NPV of the system is calculated of about 4.800.000€ during the years of 2009 to 2029. The incomings which are calculated as the sum of the incomings of natural gas and the incomings of the selling of the micro turbine's electricity generation to the national grid for each year are increased significantly every year. Similarly, the cash flows for each year which are calculated by the difference between the incomings minus the maintenance and operation costs are increased too. Figure 7-2 presents the diagram of the incomings and cash flows for the coupling system of the cheese whey anaerobic digestion treatment system and the micro turbine T350.

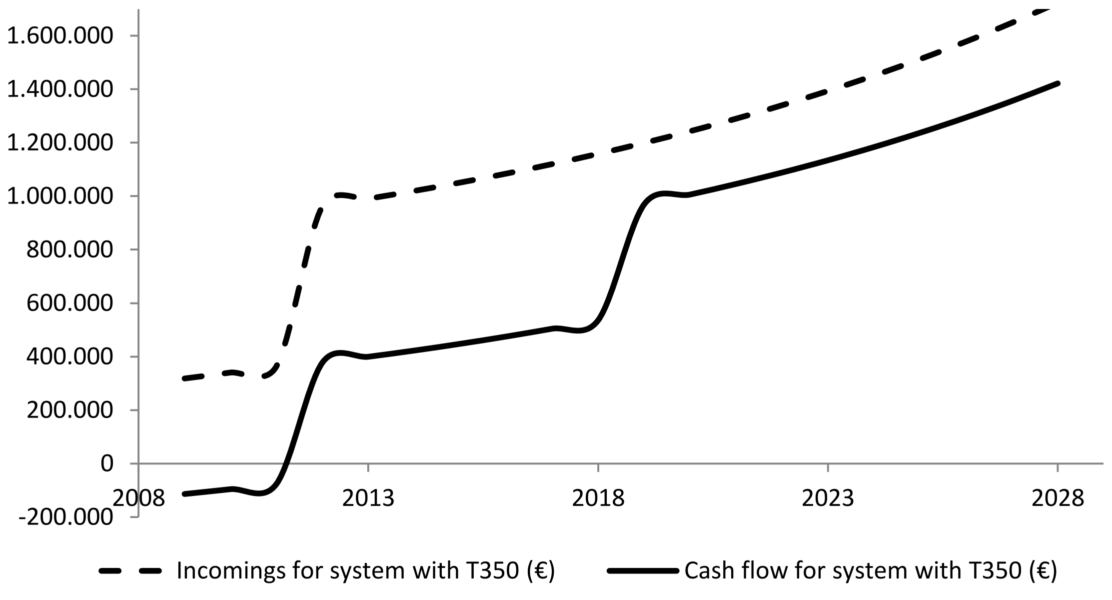

Figure 7-2 Incomings and cash flows diagram for the system in scenario 2

This diagram (Figure 7-2) illustrates a significantly increase of the incomings and cash flows values for the system of this approach. More specifically, in the year of 2013 when the micro turbine was integrated into the system of the cheese whey anaerobic digestion treatment the values of both parameters were spectacularly increased, as expected. This fact is due to the incomings from the electricity generation selling to the public grid in a quite high price. Further noticeable increase in the cash flow is observed after the year of 2019 when the company's investment loan repayment will have been completed.

7.5 Results from the economic analysis

Using the NPV method the cash flows and the incomings have been estimated for each year from 2011 to 2029 for the systems described in both of two scenarios examined in this thesis. The above economic analysis concluded that the systems examined in both of two scenarios are viable investments with a high value of NPV.

However, in order to obtain a clearer picture about the economic viability of the systems resulted; it has been decided to compare these systems with the initially cheese whey anaerobic digestion system without micro turbine using. For this reason the above diagrams (Figures 7-2 to 7-4) have been made.

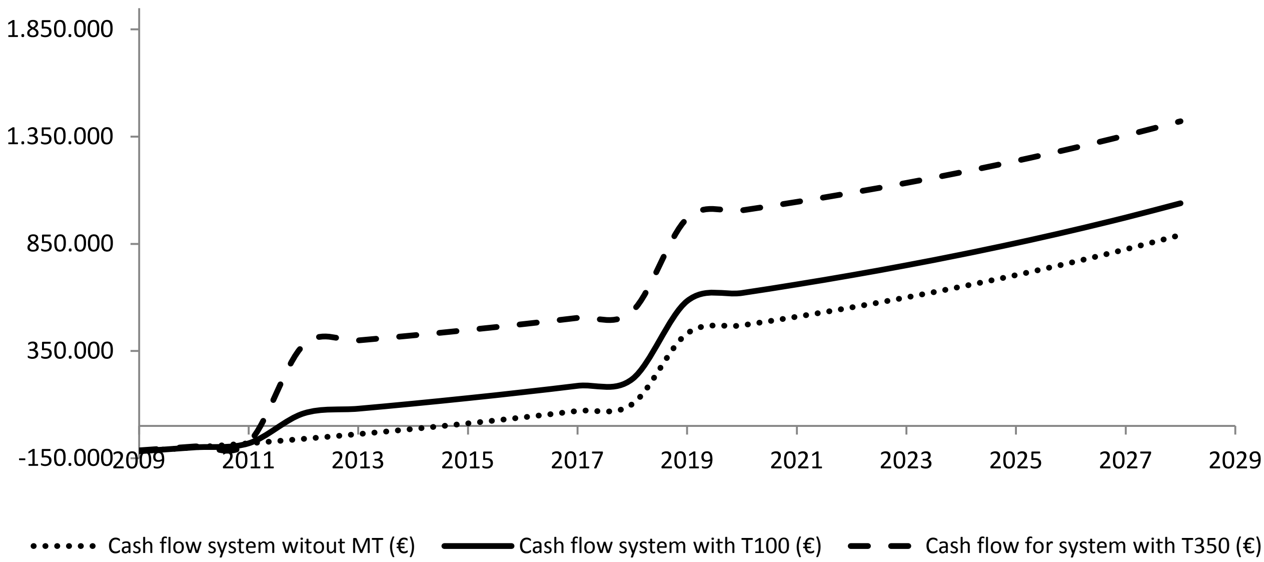

Figure 7-3 Comparing Diagram for the cash flows of the system with MT T100 & T350 and without MT

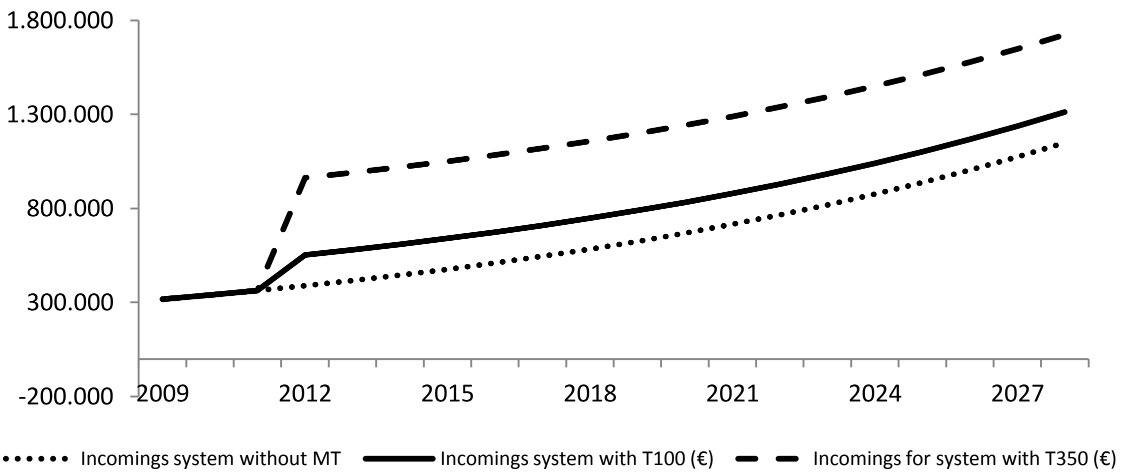

Figure 7-4 Comparing Diagram for the incomings of the system with MT T100 & T350 and without MT

From the graphs above (Figures 7-3 & 7-4), it can be observed that the size of the micro turbine has a significant impact on the economic viability of the cheese whey anaerobic digestion treatment system. The system with the incorporation of the micro turbine T350 presents almost double cash flows and incomings compared to those of the initially system without micro turbine using (Figure 7-5). This is mainly due to the high selling price of the electricity to the national grid. Both of these values incomings and cash flows are increased every year. However in the year of 2013, it has been observed significantly increase due to introduction of the micro turbines in the anaerobic digestion system, as it is expected. As it can be observed from the below diagram the NPV of the system with the incorporation of the T350 is significant higher than the system without micro turbine.

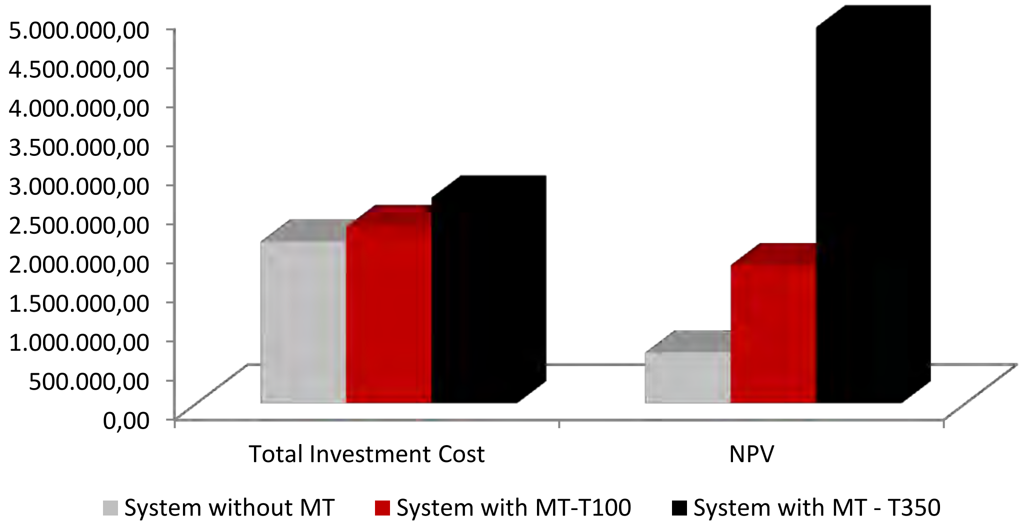

Figure 7-5 Comparing Diagram for the total investment cost and NPV of the system with MT T100 & T350 and without MT

From the economic analysis was revealed that both of these investments are profitable for the company, with high savings and incomes from the first year of its operation. Thus, the anaerobic treatment of high strength waste such as whey 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. Moreover the best economically profitable solution for the factory constitutes the usage of the whole biogas produced through the anaerobic digestion system only for electricity generation due to the present high value of the sold electricity to the national network.

Chapter 8 Parametric analysis and optimization

In this chapter a methodology to improve the performance of the CHP coupling system of the cheese whey anaerobic digestion system and micro turbine for the whole operating range is proposed. The method suggests a way for optimizing mainly the components of the micro turbine system since the cheese whey anaerobic digestion system is consider steadily. It is based on the search of the isentropic efficiencies of the biogas and air compressors, the air compressor pressure ratio, the isentropic efficiency of the gas turbine, the air temperature at the output of the recuperator and the gases temperature of the micro turbine combustion chamber. The effects of these parameters on the system's total exergy efficiency and total NPV are studied.

8.1 Introduction

An important issue when designing a CHP coupling system of anaerobic digestion system and micro turbine is the selection of design parameters (such as pressures, temperatures) in order to achieve the optimal and efficient matching of the subsystems and to ensure the long lifetime and the safe operation.

The good matching between the two main subsystems (anaerobic digestion system and micro turbine) can offer a lot of advantages for such CHP system through the wastewaters treatment, such as:

- Safe operation, since the devices work within their operating limits and they are resistance to faults.
- High efficiency, since the individual systems are designed to cooperate efficiency and to ensure the best performance not only to design point, but also in other changes conditions.
- Lower maintenance costs and increased lifetime as a result of the efficient operation and the good operating conditions ensured for both of the two subsystems.
- Fuel saving and short payback period because by designing an economical system it will be possible to complete the conventional power systems.
- Reliability and availability since the good matching of the subsystems contributes to simpler system layouts.

In the present thesis the proposed optimization method is conducted through a parametric study in order to assess the operating range of the CHP coupling system of the cheese whey anaerobic digestion system and the micro turbine and select the desired operating parameters' values for achieving the optimum system efficiency at various operating points. Thus, the parametric analysis on various parameters of the systems developed in two scenarios examined in this thesis has been carried out.

Generally, the parametric analysis of an investment project involves the investigation of the impacts of varying the main parameters affecting the project within their expected levels. Real systems are always influenced by variations in some of the plant operating parameters. These variations usually cause disturbance in the plant operating conditions and hence make plant performance deviate from the nominal design conditions.

In the case of these systems of both scenarios examined, the parameters which have been selected to assess their effects on the systems performance are the isentropic efficiencies of the biogas and air compressors (for the first scenario both compressors of micro turbine and burner), the air compressor pressure ratio, the isentropic efficiency of the gas turbine, the air temperature at the output of the recuperator and the gases temperature of the micro turbine combustion chamber. Each of these parameters is examined in the design point and their effects on the system's total exergy efficiency and the total NPV are arisen.

In Table 8-1 the variations of the parameters' values examined are presented. These ranges have been selected according to the available literature [200].

The values presented in Table 8-1 are applied to both of the systems examined in two scenarios in this thesis. The results from the parametric analysis of the system of each approach are presented in following sections.

Table 8-1 Parametric values variation

Parameters		Values variation
Biogas Comp. isentropic efficiency	n_{biogas}	0.75-0.9
Air Comp. isentropic efficiency	n_{air}	0.75-0.9
Pressure ratio	PR	2-5.4
Turbine isentropic efficiency	n_{turb}	0.75-0.92
Turbine inlet temperature (K)	T_{28}	1,100 -1,300
Air temperature at the output of recuperator (K)	T_{13}	720 - 900

8.2 Parametric analysis and optimization of scenario 1

The parametric analysis of the system described in the first scenario is carried out. As it has been referred, the examined system is a coupling system of the cheese whey anaerobic digestion system and the micro turbine T100. The values for the various parameters presented in Table 8-1 are applied to the simulation model and their effects on the total exergy and NPV of the system are described below.

8.2.1 Biogas compressor isentropic efficiency parameter

Figure 8-1 shows the graph depicting the effect of variation in the biogas compressor (comp3) isentropic efficiency on the system's total efficiency and NPV.

It is obvious that the higher values of the biogas isentropic efficiency have negative effects on the system as the total exergy efficiency is slightly reduced. This is due to the fact that an increase in the biogas isentropic efficiency value leads to an increase in the fuel supplied to the burner. This means that any consumption increase has an impact on the total exergy efficiency.

However, the higher value of the biogas compressor isentropic efficiency leads to a reduction of the consumed electricity used for the system operation which is expressed through an increase in NPV, as illustrated in Figure 8.1.

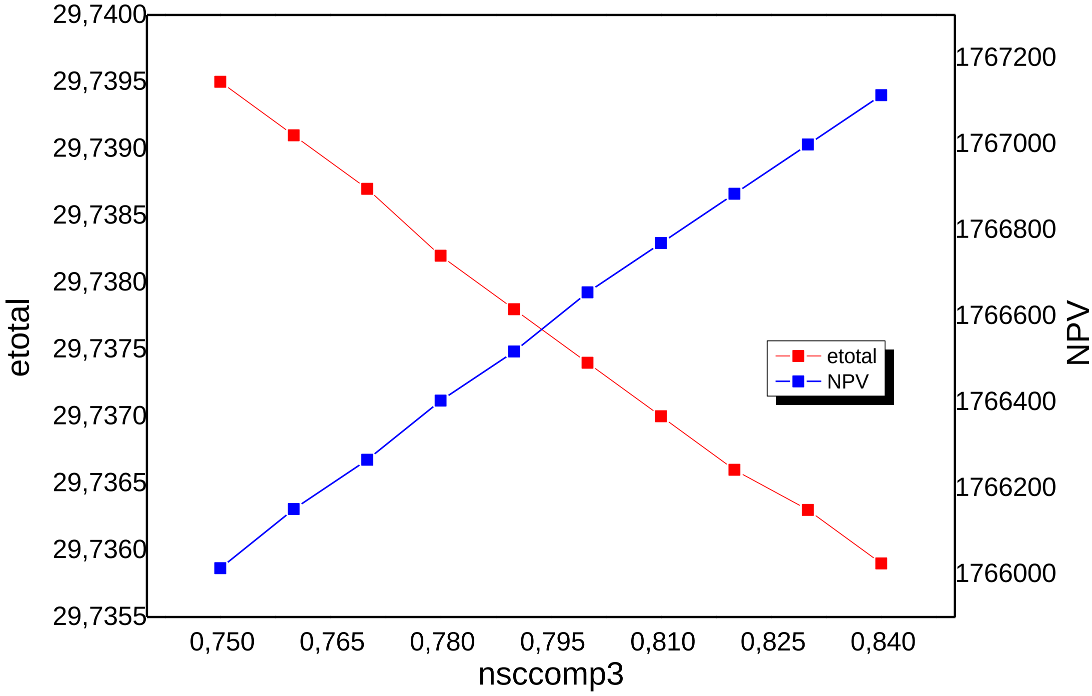

Figure 8.1 Effect of Variation in $n_{scbiogas}$ on Total Exergy Efficiency and NPV

8.2.2 Air Compressor (comp 4) isentropic efficiency parameter

At this point the air compressor (comp 4) isentropic efficiency impacts in the system are studied. The increase in air isentropic efficiency have also negative effects on the system operation as the total exergy efficiency of the system is reduced as illustrated in the Figure 8.2. However, this increase leads to a reduction of the electricity consumed for the system operation**.**

Thus, the increase in air compressor (comp4) isentropic efficiency has good effects on the NPV of the total system, as it has been presented in Figure 8.2.

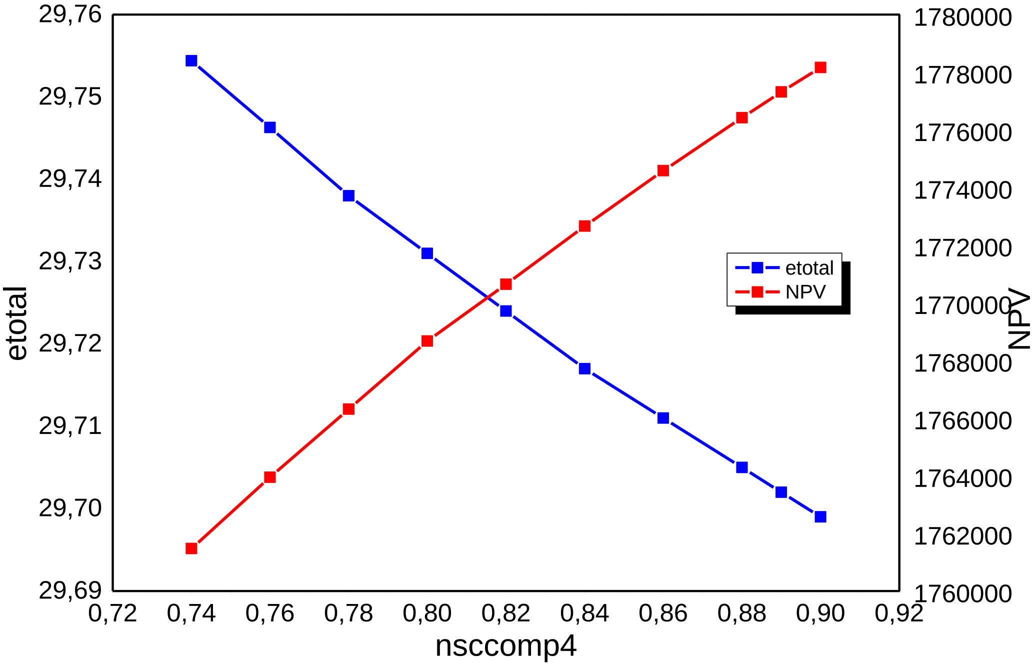

Figure 8.2 Effect of Variation in nscaircomp4 on System's Total Exergy Efficiency and NPV

8.2.3 Pressure ratio of the turbine's air compressor

In this subsection the effects of the pressure ratio of the micro turbine's T100 air compressor is studied. It is obvious that the variation of this parameter affect significantly the system operation. As it can be seen from the graph below (Figure 8.3) higher pressure ratio leads to higher total exergetic efficiency of the system, which is a result by less fuel supplied to the gas turbine cycle. This means that any saving in the fuel supplied has a significant impact on the total exergy efficiency of the system.

Additionally, this increase in air compressor pressure ratio has positive impact on the NPV value due to a reduction of the electricity used for the whole system's operation.

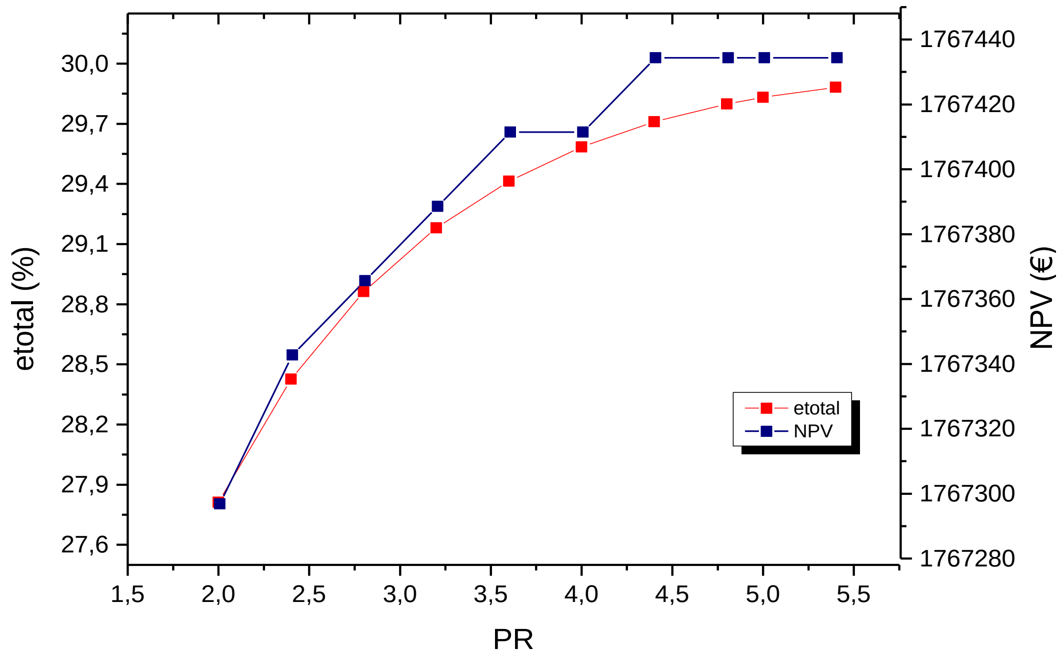

Figure 8.3 Effect of Variation in PR on System's Total Exergy Efficiency and NPV

8.2.4 Turbine isentropic efficiency

The results of the turbine isentropic efficiency values' variation on the total exergy efficiency and the NPV of the whole system are illustrated in the below graph (Figure 8.4).

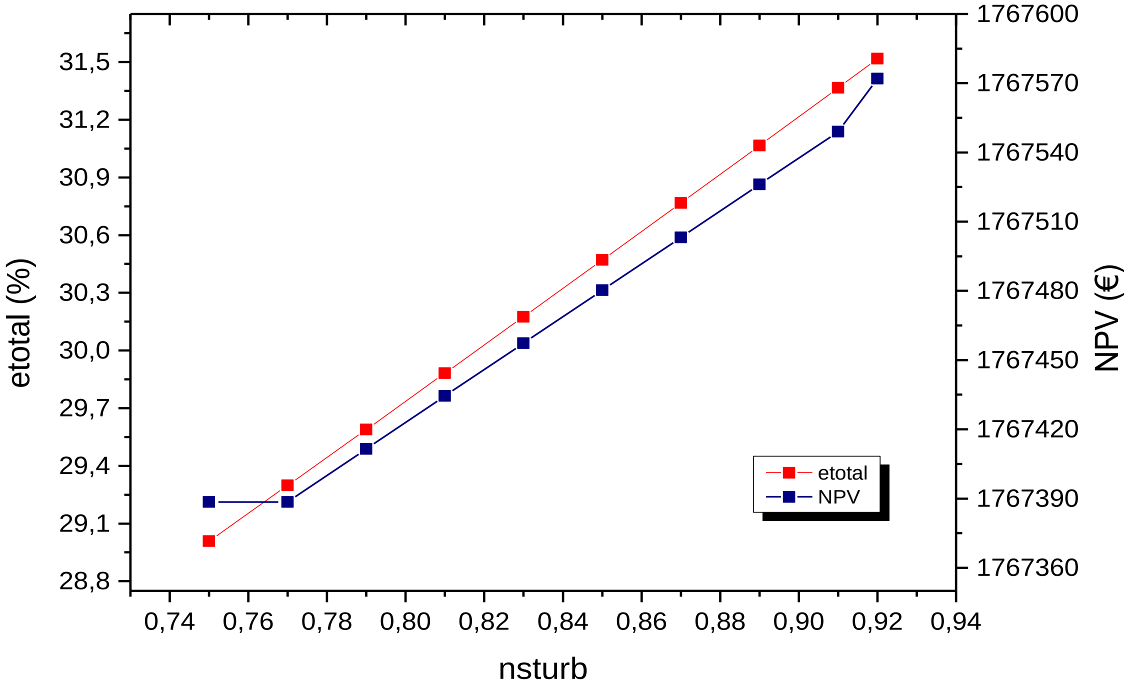

Figure 8.4 Effect of Variation in nsturb on System's Total Exergy Efficiency and NPV

As it has been expected the increase in the turbine isentropic efficiency has positive effects on the system operation. More specifically an increase in the turbine isentropic efficiency leads to an increase in the system's total exergy efficiency. This is due to the fact that higher turbine isentropic efficiency results in less fuel supplied and furthermore less electricity consumption for system operation. Thus, as it has been illustrated in the Figure 8.4 an increase in the turbine's isentropic efficiency leads to an increase in the NPV.

8.2.5 Turbine inlet temperature (T28)

In this subsection the effects from the increase of the gases temperature at the output of the recuperator (T28) on the total exergy efficiency of the system and the NPV are described.

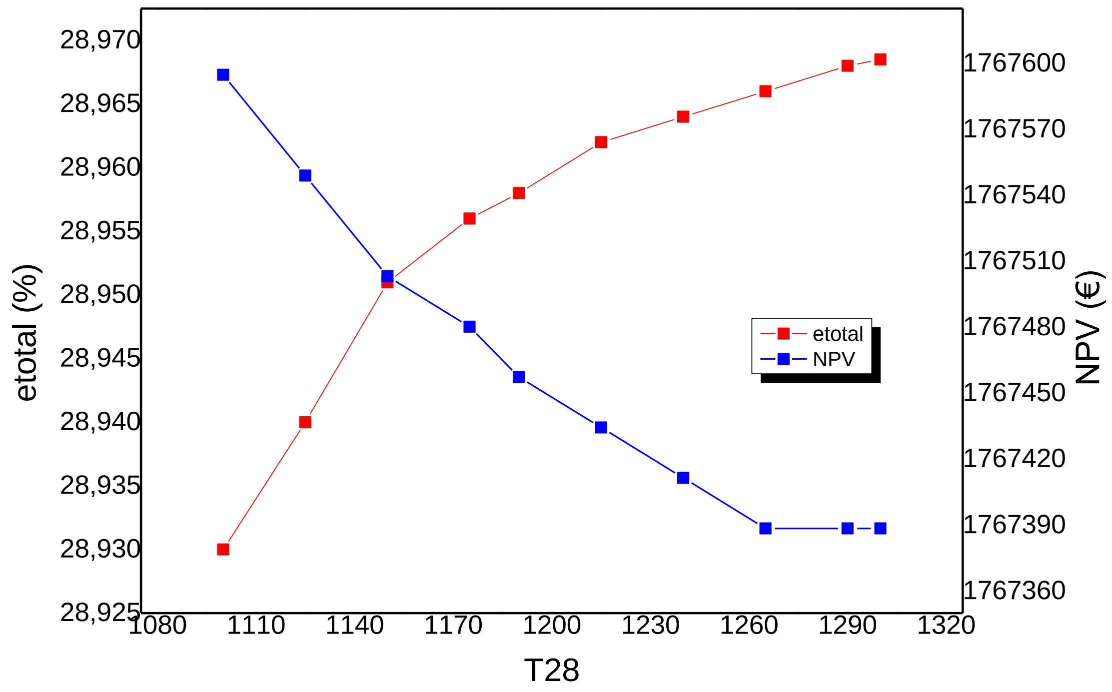

Figure 8.5 Effect of T28 on System's Total Exergy Efficiency and NPV

As it is resulted from the above graph (Figure 8.5) an increase in the gases temperature T_{28} is effective for the system. It shows that an increase in the turbine inlet temperature leads to an increase in the systems exergy efficiency due to a rise in the output power of the turbine and a decrease in the combustion chamber losses. As it has been discussed the temperature differences have significant impact on the system operation. Moreover, the increase in the turbine inlet temperature of the gases has as a result a reduction in the NPV because of the increase in energy consumption for the system operation.

8.2.6 Air temperature at the output of recuperator (T13)

The variation of the air temperature at the output of recuperator has positive effects to the system operation.

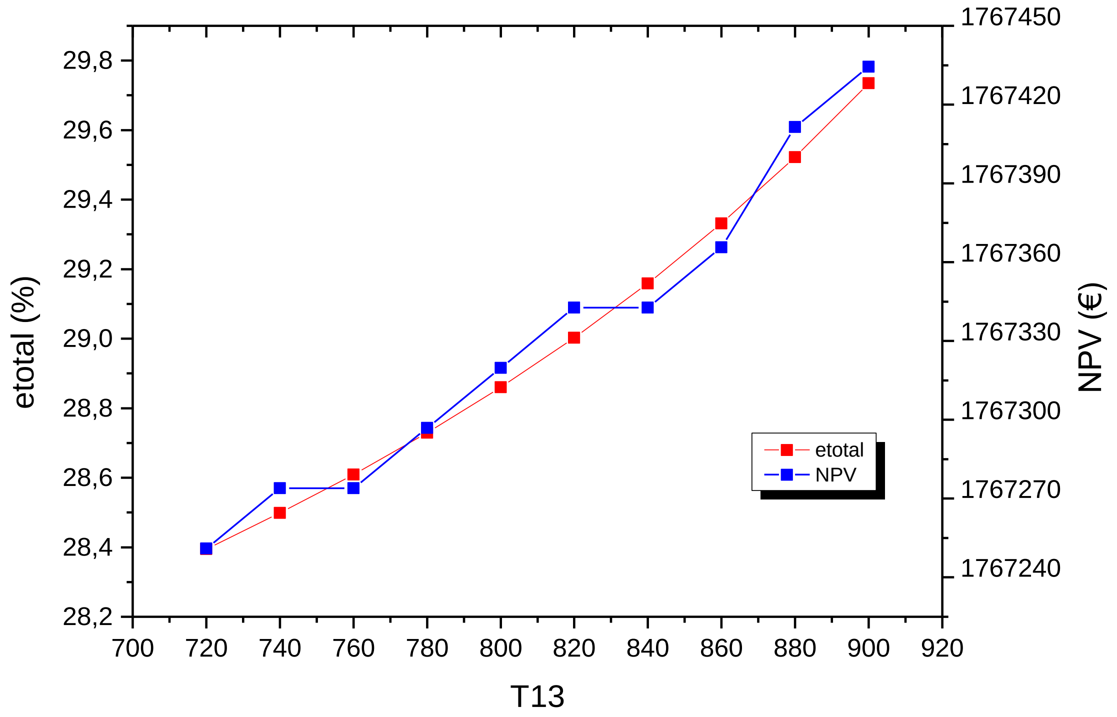

Figure 8.6 Effect of T13 on System’s Total Exergy Efficiency and NPV

As it is presented in Figure 8.6, an increase in air temperature at the output of the recuperator leads to an increase in the system's total exergy. This is due to the fact that the temperature differences between the fuel and the air supplied in the combustion chamber for burning is reduced which leads to a further reduction in combustion chamber's exergy losses. Thus, the irreversibilities in this device are reduced significantly resulting to an increase in the system's exergy efficiency. Since the turbine efficiency is increased through the increase of the air temperature T13, the power electricity consumption for the system operation is reduced as presented in Figure 8.6 through the increase in NPV value.

8.2.7 Micro turbine's Air Compressor isentropic efficiency parameter

At this point the air compressor (Comp2) isentropic efficiency impacts on the whole coupled system is studied. The increase in air isentropic efficiency has positive effects on the system operation as the total exergy efficiency of the system increases significantly (Figure 8.7). By increasing the air compressor efficiency, lower compressor work is needed. Therefore, lower value of fuel must be burnt to produce the same value of net work with consequently reducing of the electricity consumed for the system operation**.**

Thus, the increase in air isentropic efficiency has good effects on the NPV of the total system, as it has been presented in Figure 8.7.

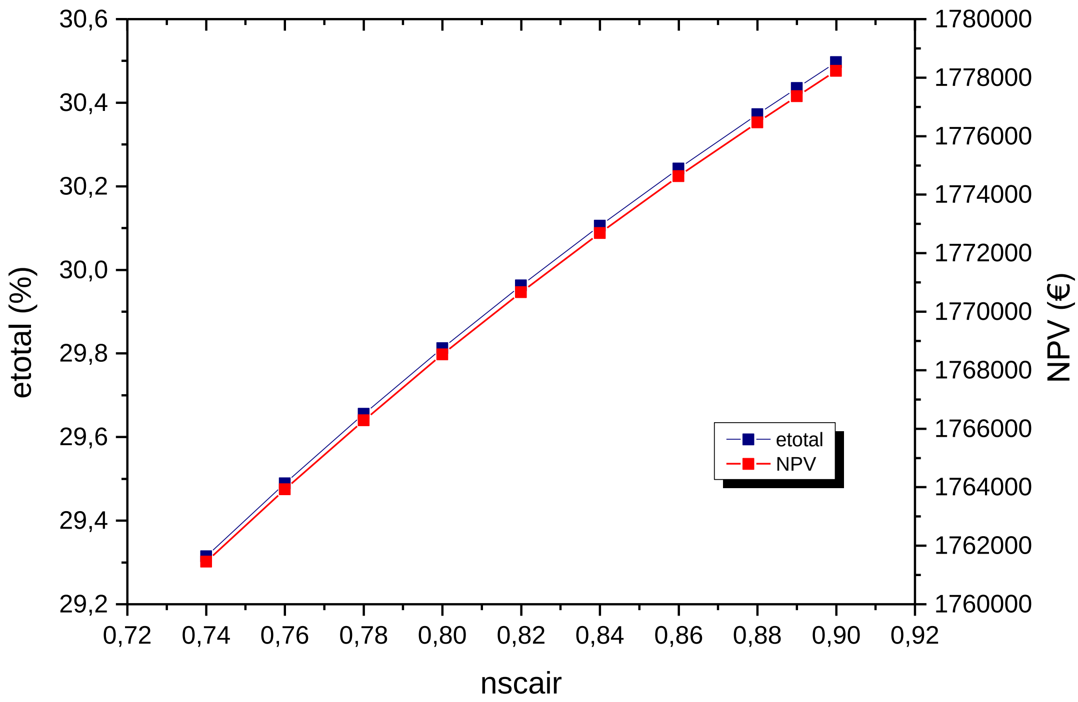

Figure 8.7 Effect of Variation in n_{scair} on System's Total Exergy Efficiency and NPV

8.3 Parametric analysis and optimization of the scenario 2

In this case also, the parametric analysis of the system described in the second scenario is carried out. As it has been referred in previous chapters, the examined system is a coupling system of the cheese whey anaerobic digestion system and the micro turbine MT350. The values for the various parameters presented in Table 8-1 above are also applied to the simulation model and their effects on the total exergy and NPV of the system are presented below.

8.3.1 Biogas compressor isentropic efficiency parameter

The total exergy efficiency, the power net, the electricity consumption, the produced steam mass and the NPV of the system influenced by variations in the biogas compressor isentropic efficiency are presented in the above Table 8-2.

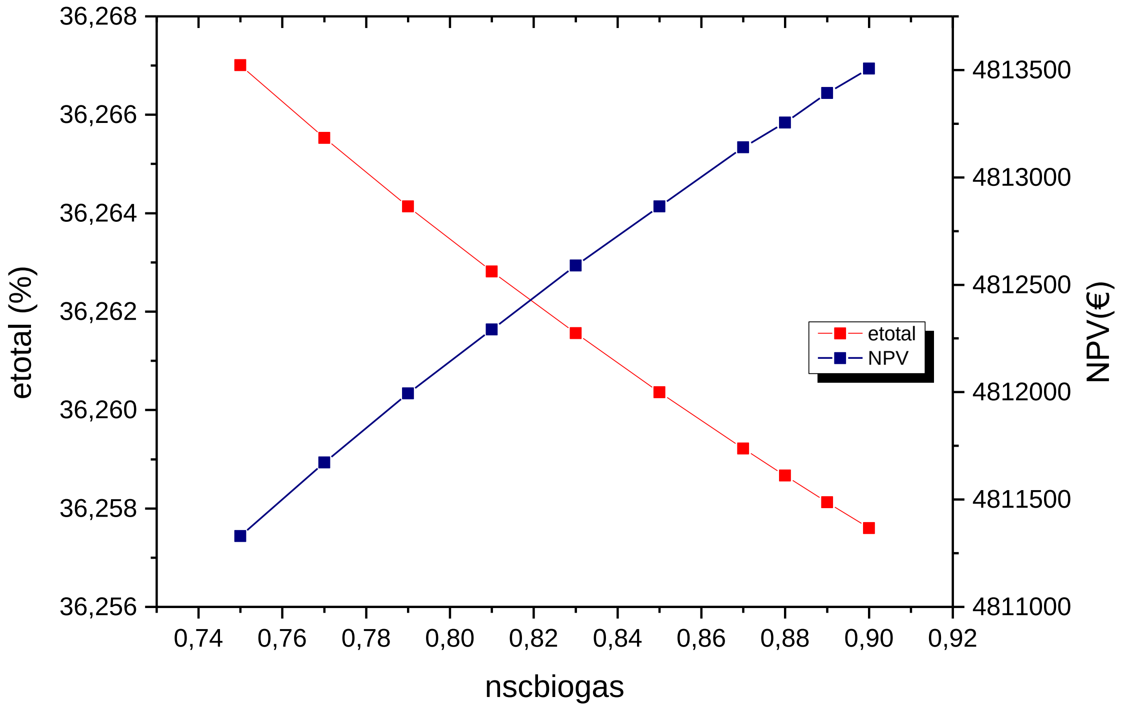

Figure 8-8 Effect of Variation in nscbiogas on Total Exergy efficiency and NPV

As it can be seen (Figure 8-8) the increase in the biogas compressor isentropic efficiency is not particularly sufficient because it leads to a slightly reduction of the system total exergy. This is due to the increase in the fuel mass flow which is supplied to the turbine combustion chamber for the system operation.

Table 8-2 Effect of variation in $n_{scbiogas}$ on Various Parameters of the system

$n_{scbiogas}$	$\dot{m}_{22}$	$\dot{W}_{total\_net}$	C_{oel}
0,75	893,04	351,5	1812
0,77	893,02	351,5	1797
0,79	893	351,5	1783
0,81	892,98	351,5	1770
0,83	892,96	351,6	1757
0,85	892,94	351,6	1745
0,87	892,92	351,6	1733
0,88	892,91	351,6	1728
0,89	892,9	351,6	1722
0,9	892,9	351,6	1717

The reason is that any increase in the fuel supplied has significant impact on the exergy destruction of the system, due to the chemical exergy of the fuel has a significant impact on his total exergy when compared to the physical exergy. On the other hand it leads to a reduction of the electricity consumption for the system operation resulting the NPV increase.

8.3.2 Air compressor isentropic efficiency parameter

At this point the effects of the air isentropic efficiency variation are described. As it can be seen through the below Table 8-3 an increase in the air isentropic efficiency leads to an increase both in the total exergy efficiency and the NPV of the system, as also presented in Figure 8-9. This is due to the fact that the higher air compressor isentropic efficiency means less work to drive air compressor and this leads to higher efficiency in gas turbine cycle.

Thus, by air compressor efficiency increasing, lower fuel and air flow is needed to the gas turbine which results in lower gas flow rate in bottoming cycle. The lower fuel value is guided to a reduction of the electricity consumed for the system operation as presented by the NPV graph.

Table 8-3 Effect of variation in nscair on Various Parameters of the system

n_{scair}	$\dot{m}_{22}$	$\dot{W}_{total\_net}$	C_{oel}
0,74	946,01	315,4	1795
0,76	927,42	328,1	1793
0,78	909,78	340,1	1791
0,8	893,01	351,5	1790
0,82	877,05	362,4	1788
0,84	861,84	372,7	1787
0,86	847,34	382,6	1786
0,88	833,49	392	1784
0,89	826,8	396,6	1784
0,9	820,25	401,1	1783

Table 8-3 shows that an increase in air isentropic efficiency leads to a further reduction of the produced steam mass flow, as it is expected. This fact is due to the reduction in the air and biogas mass flows which have as a consequent result a reduction in the gases mass flow.

The amount of the steam mass flow depends on the gases mass flow as calculated by the mass balance equation applied in the steam boiler in Chapter 5. Moreover, an increase in the system's total power production is observed, as it is expected.

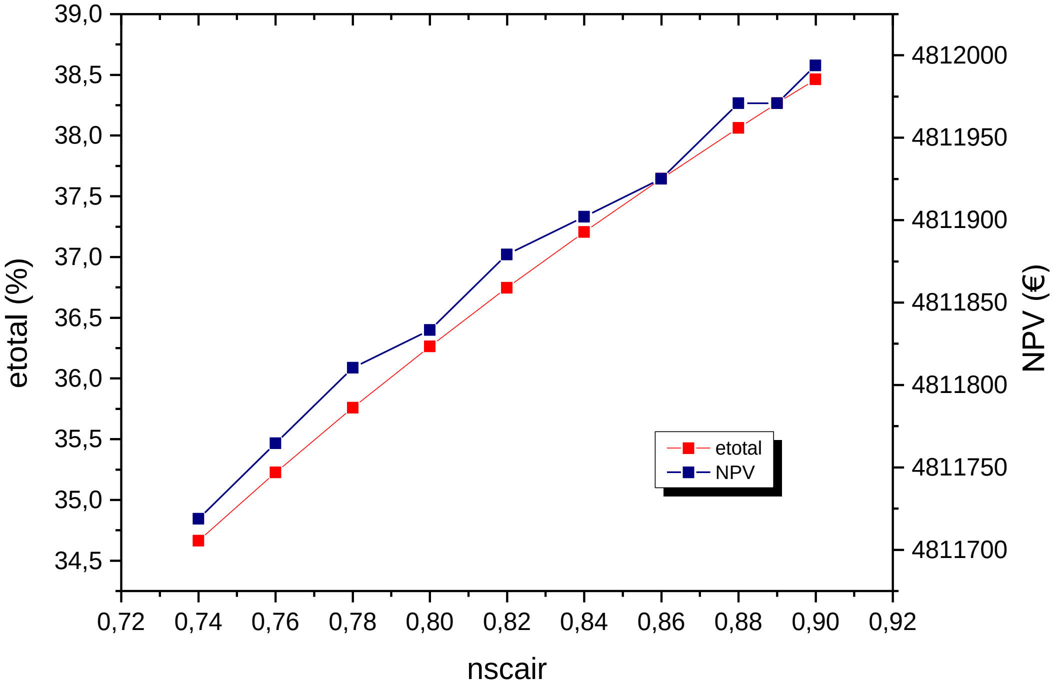

Figure 8-9 Effect of Variation in nscair on Total Exergy efficiency and NPV

8.3.3 Pressure ratio of the turbine's air compressor

It is obvious that the variation of this parameter affect significantly the system operation. As it can be seen from the graph below (Figure 8-10) an increase in the air compressor's pressure ratio causes a corresponding increase in system's total exergy due to less fuel supplied to the gas turbine cycle.

This means that any saving in the fuel supplied has a significant impact on the total exergy efficiency which is a result by the exergy destruction reduction.

As it has been referred in the previous chapter the exergy of the fuel is the sum of the physical and chemical exergy. However, the chemical exergy has a significant impact on the total exergy of fuel compared to physical exergy.

Additionally, the reduction of the fuel supplied means reduction in air mass flow and moreover reduction in gases mass flow produced. However, the reduction of the gases mass flow has a significant impact on the steam mass flow produced through the steam boiler and used to cover the industry thermal energy needs (Table 8-4). The relation between these mass flows presented in the previous Chapter 5.

Also, as it has been illustrated in Figure 8-10, the increase in air compressor pressure ratio value has a good impact on the system regarding the NPV due to the reduction of the electricity used for the system's operation.

Table 8-4 Effect of variation in PR on Various Parameters

PR	$\dot{m}_{22}$	$\dot{W}_{total\_net}$	C_{oel}
2	1096,91	212,7	1809
2,4	1026,71	260,5	1802
2,8	976,64	294,6	1798
3,2	940,08	319,5	1794
3,6	913,05	337,9	1792
4	893,01	351,5	1790
4,4	878,22	361,6	1788
4,8	867,48	368,9	1787
5	863,35	371,7	1787
5,4	857,13	375,9	1787

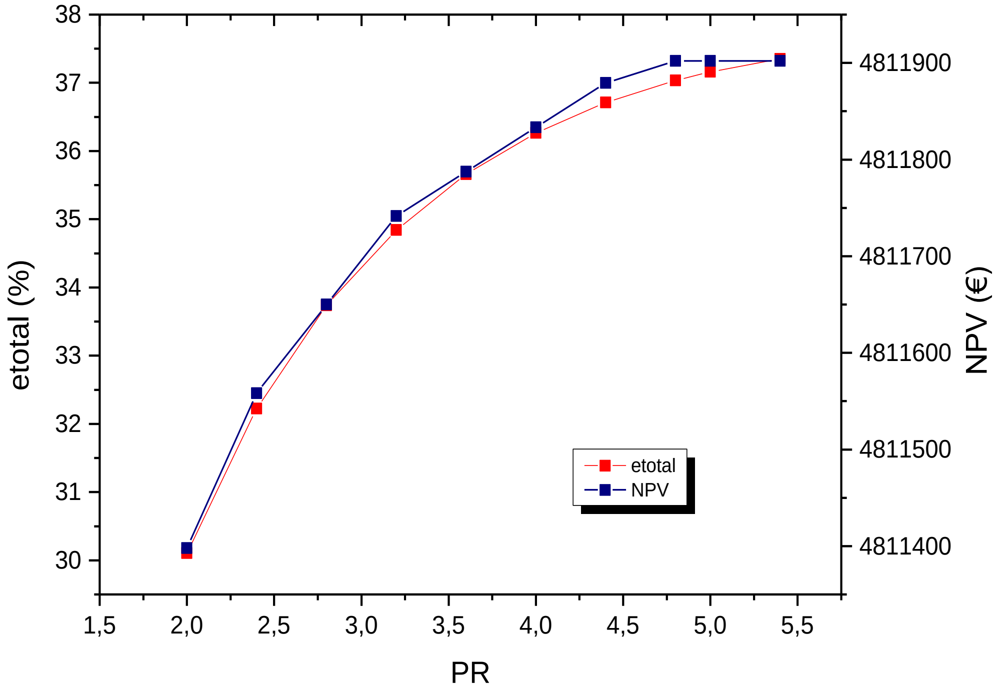

Figure 8-10 Effect of Variation in PR on Total Exergy efficiency and NPV

8.3.4 Turbine isentropic efficiency

Table 8-5 shows the effect of the variation in turbine isentropic efficiency on the produced steam mass flow, the total net power, the electricity consumption used for the system operation. It is obvious that any variation in the turbine isentropic efficiency affect significantly these parameters. More specifically, an increase in the n_{st} leads to an increase in the total net power and in a reduction both of the electricity consumption and the produced steam mass flow. This is due to the fact that an increase in the turbine isentropic efficiency value leads to a reduction of the fuel consumed for the system operation and furthermore to a reduction of the gases mass flow produced. This reduction in the gases mass flow leads to a reduction in the steam mass flow amount as calculated by the mass equation balance which is applied in the steam boiler device in Chapter 5.Regarding the total exergy efficiency and NPV it is observed an increase in both parameters, as it is expected (Figure 8-11).

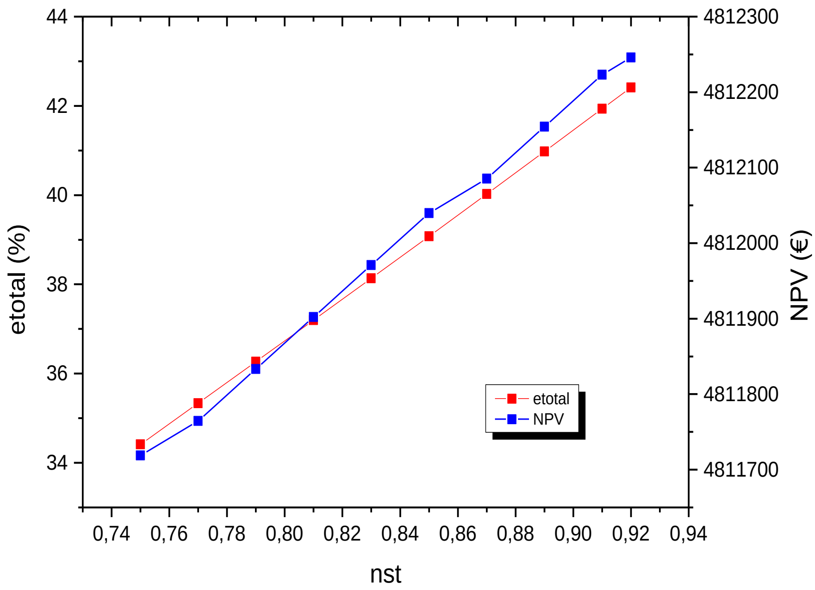

Figure 8-11 Effect of Variation in nst on Total Exergy efficiency and NPV

Table 8-5 Effect of variation in nst on Various Parameters

n_{st}	$\dot{m}_{22}$	$\dot{W}_{total\_net}$	C_{oel}
0,75	954,31	309,8	1795
0,77	923,73	330,6	1793
0,79	893,01	351,5	1790
0,81	862,14	372,5	1787
0,83	831,12	393,7	1784
0,85	799,94	414,9	1781
0,87	768,6	436,2	1779
0,89	737,1	457,7	1776
0,91	705,42	479,2	1773
0,92	689,52	490,1	1772

8.3.5 Turbine inlet temperature (T28)

At this point the turbine inlet temperature (T28) variation effects on the produced steam mass flow, the total net power are presented in Table 8-6. As it is obvious an increase in turbine inlet temperature of the gases causes an increase in produced mass flow and in electricity consumption used for the system operation.

Table 8-6 Effect of variation in T28 on Various Parameters

T_{28}	$\dot{m}_{22}$	$\dot{W}_{total\ net}$	C_{oel}
1100	709,9	369,9	1773
1125	758,24	365,1	1778
1150	799,71	360,9	1781
1175	835,67	357,3	1785
1190	855,04	355,4	1786
1215	884,23	352,4	1789
1240	910,12	349,8	1791
1265	933,24	347,4	1794
1290	954	345,3	1795
1300	961,73	344,5	1796

Figure 8-12 shows the effect of gas turbine inlet temperature variation on the system's exergy efficiency and NPV. It shows that an increase in the turbine inlet temperature leads to an increase in the systems exergy efficiency due to a rise in the output power of the turbine and a decrease in the combustion chamber losses. On the other hand, as the electricity consumption is reduced the NPV is also reduced.

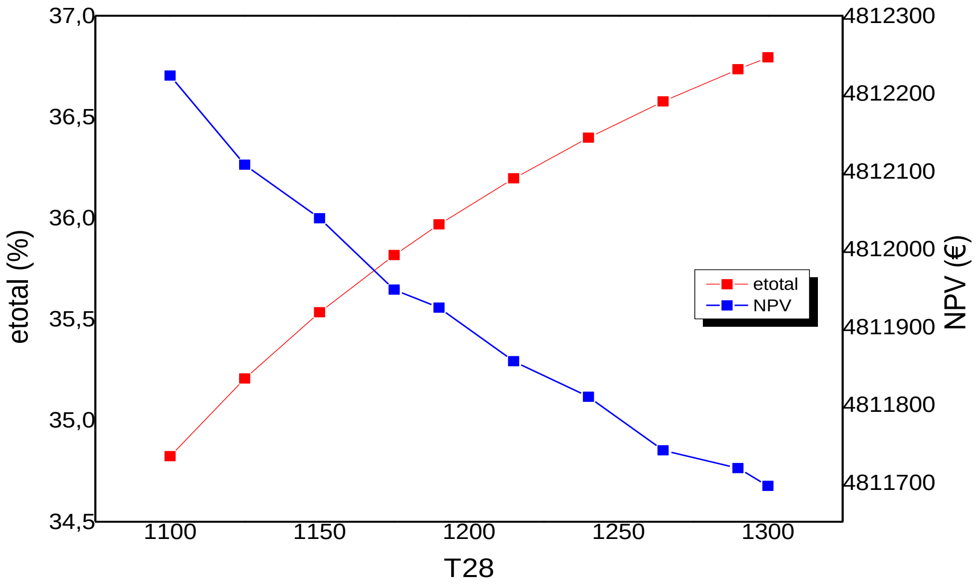

Figure 8-12 Effect of Variation in T28 on Total Exergy efficiency and NPV

8.3.6 Air temperature at the output of recuperator (T13)

The variation of the air temperature at the output of the recuperator (T13) affects the system operation. As it is presented in Table 8.7 an increase in this temperature leads to a reduction in temperature differences between the burners and the working fluid. Thus, the exergy losses in the combustion chamber are reduced.

Moreover, as it is expected the produced steam mass flow and electricity consumption using for the system operation are reduced significantly.

Table 8-7 Effect of variation in T13 on Various Parameters

T_{13}	$\dot{m}_{22}$	$\dot{W}_{total\_net}$	C_{oel}
720	1027,4	295,9	1802
740	997,79	308,2	1800
760	965,75	321,5	1797
780	930,95	335,9	1793
800	893,01	351,5	1790
820	851,45	368,6	1786
840	805,73	387,3	1782
860	755,16	407,9	1777
880	698,91	430,8	1772
900	635,91	456,4	1767

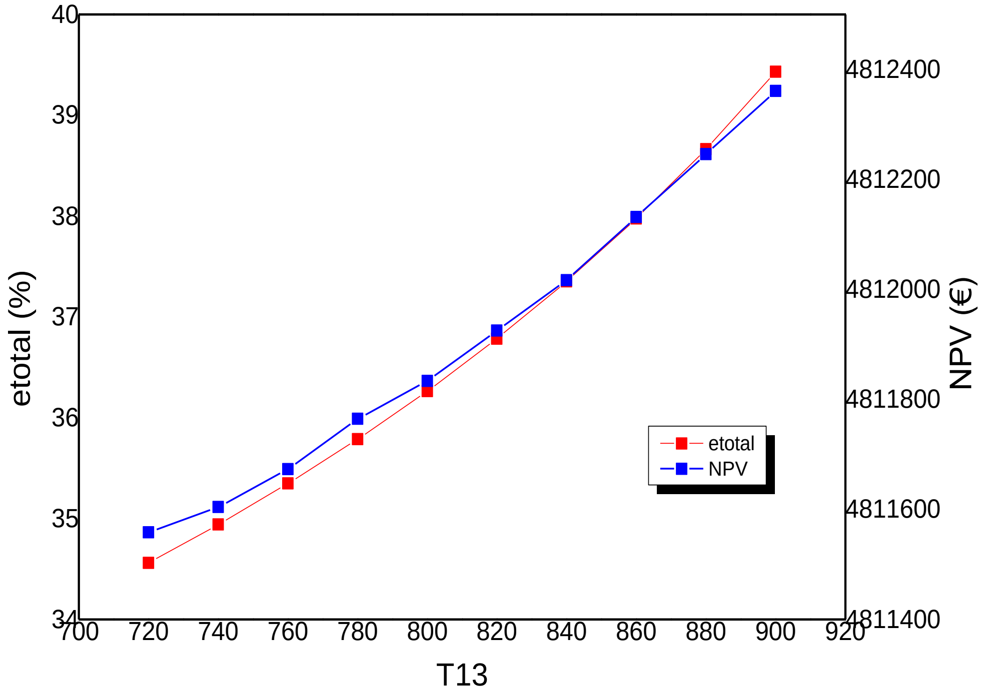

Figure 8-13 Effect of Variation in T13 on Total Exergy efficiency and NPV

Therefore, from Figure 8-13 it is presented that the increase in the air temperature at the output of the recuperator has also positive effects on the system operasion, since the total exergy efficiency of the system as well as the NPV are increased significantly.

8.4 Results from the parametric analysis

In this chapter for the simulation models obtained from the two scenarios examined a parametric analysis has been carried out. The effect of main operating parameters on the system exergetic efficiency and NPV value was studied and presented in relative graphs.

From the exergy analysis in the previous chapter 5 it is highlighted that the burner (for the 1st scenario examined) and the combustion chamber (for both scenarios examined) are constituted the most important exergy destructors in the systems. The parametric analysis is carried out in order to find the optimal values of various parameters affect the system in order to obtain optimized values of exergetic efficiency and NPV.

The parameters examined, it is decided to be the biogas and air compressor (for scenario both of micro turbine and burner) and turbine efficiencies, the air temperature after the recuperator and the turbine inlet temperature. The results show that an increase in the micro turbine air compressor and turbine efficiencies leads to an increase in the systems exergy efficiency due to a rise in the turbine output power and a decrease in the combustion chamber. Similar results it has been obtained through the increase in the value of the temperature of the air after the recuperator. Moreover the increase in the value of these referred parameters leads to a corresponding increasing of the NPV value.

On the other hand, for the system obtained from the first scenario examined the increase in the air and biogas compressor have negative impact on the exergy efficiency of the whole system as an increase of these values leads to the exergetic efficiency reduction.

Furthermore, the results from the parametric analysis highlight that any optimization in the combustion chamber of the micro turbine which means a reduction of exergy destruction leads to a more efficiently system.

Chapter 9 Results and discussion

This thesis investigates mainly, the applications of micro turbines in conjunction with Anaerobic Digestion treatment of cheese whey wastewaters obtained from cheese making process in dairy industries. A special case of an anaerobic digestion system operated in a dairy industry coupled with a gas micro turbine is examined both by exergetic, economic and parametric analysis.

Although, in the literature a plethora of studies can be found dealing with whey anaerobic digestion systems focusing mainly on the parameters which affect the process of anaerobic digestion, the COD removal and the biogas production rate (for more details see the literature review above in Section 2). However, the number of studies on the utilization of biogas systems to produce energy (heat and electricity) from whey wastewaters is limited [13, 14] in comparison to other waste types [15-21]. Also, these systems examined mainly the system of the micro turbine fueled by the biogas without provide information pertaining the anaerobic system as it is presented in this thesis.

Moreover, in order to evaluate the state of technology concerning the COD removal rate ability and the biogas production from cheese whey anaerobic digestion treatment through different types of reactors and systems in use, a common comparative basis was established and corresponding graphs are illustrated.

The main results coming from this work can be summarized as follows:

1. Through a thorough review of the literature pertinent to anaerobic digestion treatment methods, which have been used on pilot and laboratory scale for cheese whey treatment, it is concluded that the anaerobic digestion process is the most suitable process for the cheese whey treatment with high biogas production and COD removal rate. Moreover, a UASB type reactor is the most common reactor configuration employed for cheese whey wastewater treatment, mainly because of its ability to treat large volumes of effluents in a relatively short period of time.
2. A model was developed for the simulation of an Anaerobic Digestion system coupled with micro turbine using the commercially available Engineering Equation Solver process simulator.
3. Two scenarios examined. The first scenario examined the incorporation of a commercially available gas micro turbine to the system for electricity production from the combustion of a part of biogas produced. In this case the selection of the appropriate micro turbine occurs in order to achieve the maximum electricity generation while the plant requirements in steam are covered. Then in the second scenario, the case for the maximum electricity production without any limitation in the steam production is examined.
4. The matching of the Anaerobic Digestion system for cheese whey wastewaters treatment coupled with five different micro turbines was studied in order to find the

optimal configuration for the system of the first scenario. For the second scenario firstly the maximum possible electricity production has been calculated and then the most suitable micro turbine was chosen. Design point for each system examined was determined based on the micro turbine data and the data comes from an existing industry regarding the Anaerobic Digestion Plant. Moreover, for the second scenario a parametric analysis has been carried out in order to find the best value of some unknown parameters. The results have shown that the micro turbine T100 for the system of the first case and T350 for the system of the second case constitutes the optimum solutions among the others examined.

5. A validation of the models obtained for each of the two scenarios examined was also performed. The results revealed that there is a rather satisfactory agreement between expected (from the manufacturer) and calculated performance parameters for the selected micro turbines at design point conditions. However, the systems obtained are quite marginal in terms of biogas produced and the technical features of the Anaerobic Digestion system which are based on realistic data, so the coupling is approved as a quite difficult case.
6. Exergetic analysis was performed and shows that the burner for the system of the first scenario and combustion chamber for the second scenario are the devices with the highest destruction rates. Also in both systems, a large amount of exergy loss is observed in the steam boiler device due to the high temperature differences of the fluids. Suggestions were done in order to reduce the irreversibilities of both systems studied.

7. An economic analysis was carried out based on the NPV method, which revealed that both of these investments are profitable, with high savings and incomes from the first year of its operation. Moreover, the system with the incorporation of the micro turbine T350 presents almost double cash flows and incomings compared to those of the initially system without micro turbine incorporation.
8. A study to achieve an improved performance in the whole operating range of the cheese whey anaerobic digestion system coupled with micro turbine for both of two cases studied was carried out through parametric analysis. The results show that the mainly parameters which affect positive the exergy efficiency and the NPV of both of the two systems examined in two scenarios were the air compressor and turbine isentropic efficiencies and the temperature of the air after the recuperator.

The system developed in this thesis is composed of two parts. The first part ends with the production of the biogas produced through the anaerobic digestion system and the second part deals with the use of the biogas with a micro turbine in order to generate energy.

Therefore, the system could be characterized as quite flexible since it could be coupled with several other types of distributed generation technologies, such as fuel cells, hybrid systems, internal combustion engines etc. At present, it seems that the internal combustion engine is the most suitable technology with efficiencies exceeding those obtained with a micro turbine. From the analysis presented in the Appendix 1, it can be shown that with the use of an reciprocating internal combustion engine with efficiency of the order of 40%, replacing the micro turbine in the system examined in scenario 2 (as described in Chapter 4.3), a maximum energy production of about 800 kW can be obtained with a total exergy efficiency of about

60%. Consequently, taking into account that the corresponding values for the system examined in scenario 2 with the use of micro turbine T350 are significantly lower (350 kW and 36%, respectively), the internal combustion engines appears to constitute the optimal solution for energy production.

Although the micro turbine technology is not yet a mature technology and a viable option (lower efficiencies per 20-25%) today compared with the thermal engines, this technology, however, seems to be a promising method for generating both power and heat under certain circumstances and their use is expected to increase in the near future.

The other alternative technologies of distributed generation (fuel cells, hybrid systems etc.), mentioned previously but not covered in this thesis, may be considered for further elaboration and investigation

The baseline system studied in this thesis operates at steady state, full load of the turbine. However, the nature of this system, that is, the production of an intermediate energy carrier (biogas) that can be conveniently stored in a tank, allows for an intermittent system operation. Therefore, the micro turbine may be switched on and off according to the need to produce electricity, or availability of biogas. This can constitute another approach that can be examined in the future with the developed model, by raising the condition of biogas production and micro turbine fuel consumption. Furthermore, the model developed can be used to study the performance of different designs of cogeneration systems, such as configurations with separate power turbine, arrangements incorporating, intercooling or heating etc.

The model by utilizing the experience gained from the present thesis, it will be a useful tool to study critical operations such as emergency shutdown or startup under different control methods and it could be applied to study other waste type treatment plants for energy production.

In conclusion, since the cheese whey is a major pollutant, but simultaneously an important energy source, utilization for clean energy (biogas, methane and hydrogen) production is of paramount importance. Therefore, further research in the field of exploitation and management of cheese whey, together with the development of new technologies for its treatment, is necessary. To this end, the development of technologies for hydrogen production from cheese whey wastewater, particularly by acidogenesis is currently worth investigating. The dark anaerobic digestion processing for cheese whey treatment has been proved a suitable method for direct H_2 production on lab-scale. Further research is required also to evaluate the performance of this process on a larger scale. Also, the direct use of cheese whey in fuel cells for production of electricity seems to be a promising option.

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Appendix 1 - Case study

The system of cheese whey anaerobic digestion coupled with an Internal Combustion Engine

In this Appendix, the use of the internal combustion engine (ICE) instead of the micro turbine technology examined in the scenario 2 of this thesis, coupled with the anaerobic digestion system of cheese whey is studied as an alternative solution of distributed generation technology. Therefore the system presented in the scenario 2 is converted as illustrated in the flow chart below (Figure 1). The efficiency of the internal combustion engine is considered equal to 40% approximately.

The system was developed using EES program. For the system analysis the assumptions have been made and presented in the above Chapter 4.4 are in valid. Moreover it is considered that only 40% approximately, of the total heat supplied to the engine in the form of fuel is converted into useful work while the remaining amount concerns the losses due to the friction (as the internal parts of the engine move, they rub against each other and lose energy due to friction) and the engine cooling system (30%) and the heat expelled to the environment through exhaust gases (30%)[201]. Therefore, the exergy of the water for the engine cooling

(T=85° C) is considered as non exploitable. The biogas mass flow is equal to 7,700 kg/hr. The exhaust gases immediately leaving the engine to the temperature of about 400° C.

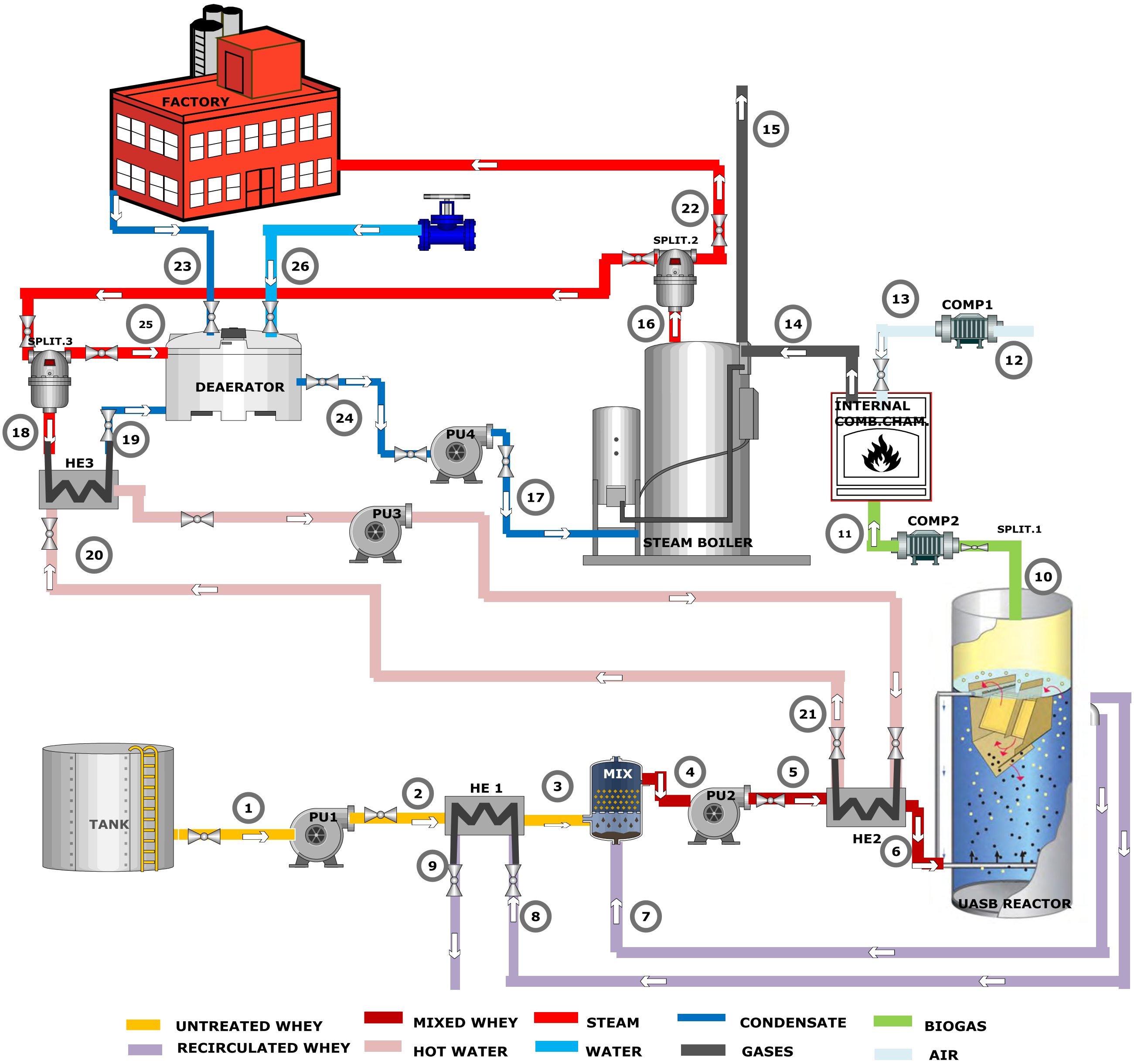

Figure - 1 Flow chart of the CW AD system coupled with an internal combustion engine

Then the gases are guided to the steam boiler and following the system operation is remaining as described in Chapter 4. Because the state of water in the exhaust is generally vapor in internal combustion engine, the lower heating value (LHV) of the biogas is used.

The efficiency of the engine is given from the below equation (1):

$$e_{ICE} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{\dot{W}_{ICE}}{\dot{m}_{f} * LHV} \quad (1)$$

From this relation (1), the maximum energy production is calculated equal to 800kW, approximately. The plant produces electrical energy simultaneously with steam which is used in order to cover part of industry’s thermal needs. The electricity is generated by the engine actuated generator set. The biogas engine – generator sets produce of about 720 kW electricity at 100% output and 657kg/hr steam through the steam boiler (Table – 1).

The model developed with the use of the equations given in Chapter 5 and Chapter 6.1. Therefore, the mass flow, temperature enthalpy, fluid condition and total exergy at each state of the system are given in Table 1.

For the exergetic analysis the relations presented in Chapter 6.1 have been used. The differences which are observed in the system of this case study compared to that examined in the previous Chapter 6 concern the calculation of the exergy efficiency and exergy destruction of the engine and therefore for the whole system. Thus, the exergy efficiencies and exergy destructions rates at each component of the system are calculated through the relations presented in the Table 2 below.

Table 1 Mass flow, temperature, pressure, enthalpy, entropy, exergy and fluid condition at each state of the system.

State	Fluid Condition	ṁ(kg/hr)	T(K)	P(bar)	h (kj/kmol)	s(kj/kmol K)	Ė(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	1526,3
3	Untreated Whey	6341,7	302,15	1,038	-8450	16,675	1526,4
4	Mixture	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
7	Recycled whey	4991,4	308,15	1,038	2612	9,08	63,65
8	Treated whey	6046,8	308,15	1,072	2612	9,08	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	7427,3	298,15	1,013	-4713	199,13	-0,59
13	Air	7427,3	312,15	1,163	-4302	199,328	24,74
14	Gases	7700	660	1,163	-58233	225,291	381,97
15	Gases	7700	450	1,013	-64697	214,576	136,71
16	Steam	743	453,1	10,013	50044	118,647	169,5
17	Condensate	743	375,15	10,013	7714	23,938	8,06
18	Steam	66,8	416,89	4,013	49339	124,224	12,8
19	Condensate	66,8	375,15	1,088	7702	23,951	0,71
20	Hot water	4985	343,15	2,513	5282	17,202	21,56
21	Hot water	4985	335,78	1,013	4724	15,566	16,15
22	Steam	656,8	453,1	10,013	50044	118,647	149,84
23	Condensate	500	375,12	1,088	7700	23,946	5,3
24	Condensate	743	375,12	1,088	7700	23,946	7,88
25	Steam	19,3	375,12	1,088	48262	132,075	2,69
26	Fresh water	223,6	298,15	1,088	1889	6,611	0,16

Table 2 Exergy destructions rates and exergy efficiencies

Component		Relation	Value
Pump 1	$\dot{E}_{des,p1}$	$-\dot{W}_{p1} + \dot{E}_1 - \dot{E}_2$	0,20 kW
	$\dot{e}_{ex,p1}$	$(\dot{E}_2 - \dot{E}_1)/(-\dot{W}_{p1})$	31,42 %
Heat Exchanger 1	$\dot{E}_{des,HE1}$	$\dot{E}_2 + \dot{E}_8 - \dot{E}_3 - \dot{E}_9$	0,99 kW
	$\dot{e}_{ex,HE1}$	$(\dot{E}_3 - \dot{E}_2)/(\dot{E}_8 - \dot{E}_9)$	8,91%
Mixing unit	$\dot{E}_{des,MIX}$	$\dot{E}_3 + \dot{E}_7 - \dot{E}_4$	10,46 kW
	$\dot{e}_{ex,mix}$	$(\dot{E}_4)/(\dot{E}_3 + \dot{E}_7)$	99,34%
Pump 2	$\dot{E}_{des,p2}$	$-\dot{W}_{p2} + \dot{E}_4 - \dot{E}_5$	0,31 kW
	$\dot{e}_{ex,p2}$	$(\dot{E}_5 - \dot{E}_4)/(-\dot{W}_{p2})$	44,92%
Heat Exchanger 2	$\dot{E}_{des,HE2}$	$\dot{E}_5 + \dot{E}_{20} - \dot{E}_6 - \dot{E}_{21}$	4,25 kW
	$\dot{e}_{ex,HE2}$	$(\dot{E}_6 - \dot{E}_5)/(\dot{E}_{20} - \dot{E}_{21})$	21,42%
UASB reactor	$\dot{E}_{des,UASB}$	$\dot{E}_6 - \dot{E}_8 - \dot{E}_{10} - \dot{E}_7$	53,03 kW
	$\dot{e}_{ex,UASB}$	$(\dot{E}_7 + \dot{E}_8 + \dot{E}_{10})/(\dot{E}_6)$	96,65%
Biogas compressor	$\dot{E}_{des,comp1}$	$-\dot{W}_{comp1} + \dot{E}_{10} - \dot{E}_{11}$	0,14 kW
	$\dot{e}_{ex,comp1}$	$(\dot{E}_{11} - \dot{E}_{10})/(-\dot{W}_{comp1})$	85,88%
Air compressor	$\dot{E}_{des,comp2}$	$-\dot{W}_{comp2} + \dot{E}_{12} - \dot{E}_{13}$	4,25 kW
	$\dot{e}_{ex,comp2}$	$(\dot{E}_{13} - \dot{E}_{12})/(-\dot{W}_{comp2})$	85,62%
Internal Combustion Engine	$\dot{E}_{des,ICE}$	$\dot{E}_{14}+\dot{W}_{ICE}/\dot{E}_{11} + \dot{E}_{13}$	204,98 kW
	$\dot{e}_{ex,ICE}$	$\dot{E}_{11} + \dot{E}_{13}-\dot{E}_{14} - \dot{W}_{ICE}$	85,49%
Boiler	$\dot{E}_{des,boiler}$	$\dot{E}_{14} + \dot{E}_{17} - \dot{E}_{15} - \dot{E}_{16}$	83,82 kW
	$\dot{e}_{ex,boiler}$	$(\dot{E}_{16} - \dot{E}_{17})/(\dot{E}_{14} + \dot{E}_{15})$	65,82%
Steam Separator	$\dot{E}_{des,st\ sep}$	$\dot{E}_{16} - \dot{E}_{18} - \dot{E}_{22} - \dot{E}_{25}$	4,17 kW
	$\dot{e}_{ex,st\ sep}$	$(\dot{E}_{18} + \dot{E}_{22} + \dot{E}_{25})/(\dot{E}_{16})$	97,54%
Heat exchanger & Pump 3	$\dot{E}_{des,HE\ P3}$	$-\dot{W}_{P3} + \dot{E}_{18} + \dot{E}_{21} - \dot{E}_{19} - \dot{E}_{20}$	7,26 kW
	$\dot{e}_{ex,HE\ P3}$	$(\dot{E}_{20} - \dot{E}_{21})/(-\dot{W}_{P3} + \dot{E}_{18} - \dot{E}_{19})$	42,69%
Deaerator	$\dot{E}_{des,deaer}$	$\dot{E}_{19} + \dot{E}_{23} + \dot{E}_{25} + \dot{E}_{26} - \dot{E}_{24}$	0,98 kW
	$\dot{e}_{ex,dearer}$	$(\dot{E}_{24})/(\dot{E}_{19} + \dot{E}_{23} + \dot{E}_{25} + \dot{E}_{26})$	88,97%
Pump 4	$\dot{E}_{des,p4}$	$-\dot{W}_{p4} + \dot{E}_{24} - \dot{E}_{17}$	0,74 kW
	$\dot{e}_{ex,p4}$	$(\dot{E}_{17} - \dot{E}_{24})/(-\dot{W}_{p4})$	20,07%

The exergy analysis results are summarized in Figure 2. As it is expected for the system examined in this case study the highest exergy destruction rate are observed in the internal combustion engine, as a result of the combustion process. The fundamental sub-processes which contribute to the combustion irreversibility include mixing, heat transfer and chemical reactions. This value reaches to 55% of the total exergy destruction. The steam boiler exhibits the next highest exergy destruction, mainly due to the temperature differences between two fluid streams passing through it, but also due to the pressure drop across the device. Also, the exergetic efficiencies of the main components, i.e. the ratio of the exergy recovered to the supplied exergy are illustrated in Figure 2. The lower exergetic efficiencies values are observed in the heat exchangers 1 and 2, as a result of the temperatures differences.

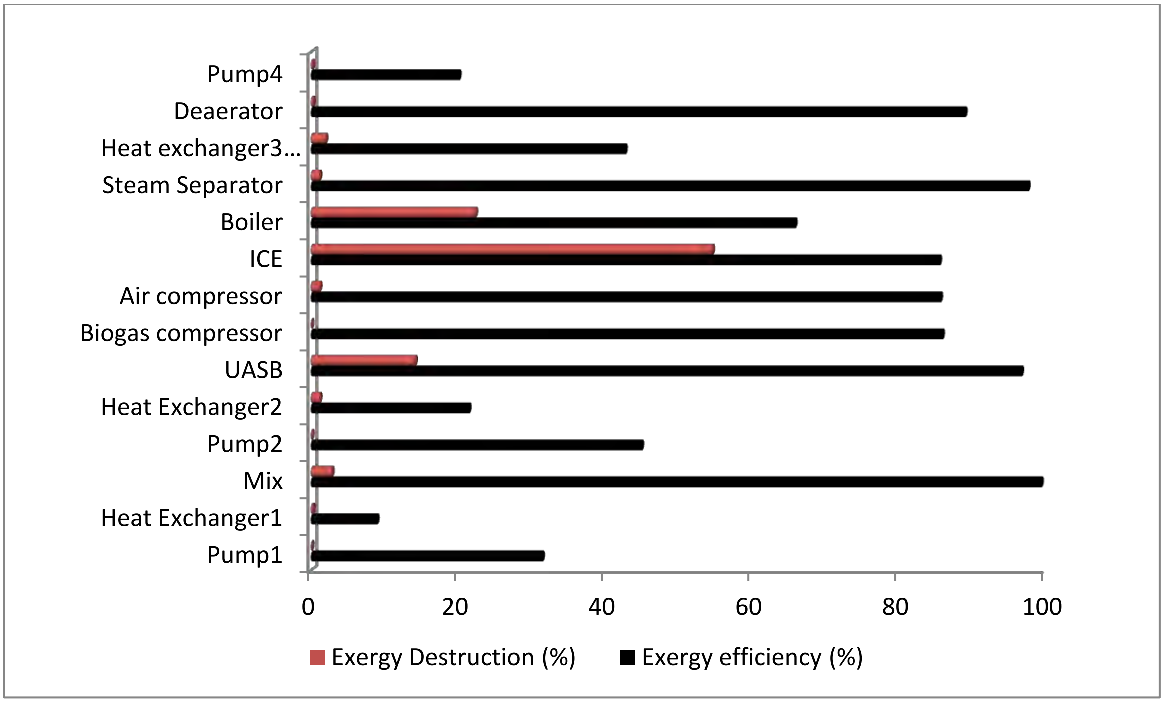

Figure 2: Exergy destruction rates and exergy efficiency for each component of the system.

In order to calculate the total exergy destruction and exergetic efficiency for the whole system examined in this case study the below relations have been taken into account.

The overall balance of the system is expressed through:

$$\dot{E}_{des,sys} = \dot{E}_{1} + \dot{E}_{12} + \dot{E}_{26} + \dot{E}_{23} + \dot{E}_{33} - \dot{E}_{9} - \dot{E}_{15} - \dot{E}_{22} - (\dot{W}_{total,spent} + \dot{W}_{ICE}) \quad (2)$$

and the total exergetic efficiency which is the ratio of the net power output to the exergy supplied to the system is given by:

$$e_{ex,sys} = \frac{\dot{E}_{22} - \dot{E}_{23} + \dot{W}_{ICE}}{\dot{E}_{1} + \dot{E}_{12} + \dot{E}_{33} + \dot{E}_{26} + \dot{W}_{total,spent}} \quad (3)$$

Therefore, for the cheese whey anaerobic digestion system coupled with an internal combustion engine, the total exergy destruction is calculated equal to 375 kW approximately and the total exergy efficiency reaches to 62%.

Appendix 2 - Short Curriculum Vitae

EDUCATION

1. **PhD Candidate,** Department of Mechanical, University of Thessaly (June 2011 – today).

Subject: Energy and exergy analysis of combined heat and power systems - wastewater treatment in dairy industries for energy production

Supervisor: prof. Stamatis G. Anastassios

2. **Postgraduate Specialization Diploma (M.Sc. Degree): "**Energy Systems, Industrial Processes and Pollution-Abatement Technologies"

Department of Mechanical, University of Thessaly (09/2009-04/2011)

Diploma degree: Excellent

3. **Diploma of Mechanical Engineering,** Department of Mechanical Engineering – University of Western Macedonia (former Aristotle University of Thessaloniki) (09/2002-05/2008)

Diploma Degree: Very good

Direction of study: Environment and energy usage – Energy planning of buildings.

AWARDS & SCHOLARSHIPS

Within the Diploma of Mechanical Engineering**:**

Award of Excellence from the State Scholarships Foundation (SSF).

Scholarship from the State Scholarships Foundation (SSF).

Within the PhD studies:

Scholarship from the Research Committee of the University of Thessaly

PUBLICATIONS

- Chatzipaschali A. Aspasia, Stamatis G. Anastassios (2012): ''Biotechnological Utilization with a Focus on Anaerobic Treatment of Cheese Whey, Current Status and Prospects''. Journal: *Energies* (5), p.3492-3525.
- Chatzipaschali A. Aspasia, Stamatis G. Anastassios (2014): Exergetic and economic analysis of a cheese whey wastewater anaerobic treatment plant with a cogeneration system. Journal: Desalination and Water Treatment, 56 (5), p.1223-1230.
- Chatzipaschali A. Aspasia, Stamatis G. Anastassios, Nikolaos Andritsos (2016): Incorporating available micro gas turbine in an anaerobic digestion system: Matching considerations and performance evaluation. Submitted for publication.
- Chatzipaschali A. Aspasia, Stamatis G. Anastassios (2012): "Anaerobic Digestion of cheese whey with focus on COD removal rate", International Conference on New Energy, Biological Engineering and Food Security, Published in Lecture Notes in Information Technology (LNIT) ISSN: 2070-1918, Hong-Kong, September 4-5, 2012.
- Chatzipaschali A. Aspasia, Stamatis G. Anastassios (2012): "Removal of polluting load and energy production from cheese whey anaerobic digestion", 1^{st} Environmental Conference of Thessaly, Skiathos, September 8-10, 2012.

- Chatzipaschali A. Aspasia, Stamatis G. Anastassios (2013): Exergetic and economic analysis of a cheese whey wastewater anaerobic treatment plant with a cogeneration system. 4th International Conference on Environmental Management, Engineering, Planning and Economics, Mykonos Island, June 24 to 28.

OTHER QUALIFICATIONS

1. English (ECCE Michigan degree)
2. Autocad (degree: European Computer Driving Licence CAD (ECDL CAD))
3. Windows- office (degree: European Computer Driving Licence (ECDL)
4. Knowledge of 4M software (E/M Designs).
5. Good use of internet
6. Knowledge of Software: SUN CODE, Method of 5000, Aspen Plus, Engineering Equation Solver (EES)
7. Seminar: ‘Saving of energy – Buildings energy efficiency’.

WORK EXPERIENCE

1. **Dates:** August 2010 - Present

Name of employer – type of business: **URS INFRASTRUCTURE AND ENVIRONMENT UK LTD - OMEK CONSULTING ENGINEERS SA**

Central Greece Motorway (E65) Independent Engineer

Position held: Engineer of E/M works

Main activities and responsibilities

Supervision of E/M works. Monitoring and checking compliance with the design requirements / specifications, quality program of testing materials, environmental terms and construction time schedule.

Translation of technical texts (Monthly Reports).

2. **Dates:** September 2010 – May 2015

Name of employer – type of business: **PERMANENT COMMISSIONED OFFICERS SCHOOL**

Main activities and responsibilities:

Teaching of the following courses:

- Vehicle engineering,
- Internal Combustion Engines
- Technical Design.
- Piston and air turbine aircraft engines

3. Dates: January 2008 - January 2010

Χώρα: Ελλάδα

Name of employer – type of business**: CYCLOTRON LTD – Consulting Engineers**

Position held: Engineer of E/M works

Main activities and responsibilities:

Conducting of E/M studies. Monitoring and checking compliance of the Projects with the design requirements / specifications. Some of the Projects:

- Four-story building of houses and shops in Aspropyrgos (street Agia Marina 29)
- New six-store residential building on pilots with basement and attic in Keratsini, Athens (street Galen 25 and Bali).
- Internal fitting out of the Athinaiki clinic (street Dorylaiou 24).
- Space Rearrangement in an office building area 3.500sq.m of Drug Company - SERVIE HELLAS LTD (National Resistance route 72 in Halandri).

4. Dates: August 2007- August 2008

Name of employer – type of business: CONSTRAT LTD - Technical & Commercial Company

Position held: Responsible of public tenders.

Main activities and responsibilities:

- Monitoring the Government Gazette and other sources, about the Public Tenders conducted by Greek Municipalities & Municipal Water.
- Preparation of technical and financial offers and collecting the necessary documents for participation.
- Representation of the company at more than 40 Public Tenders.