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COST OPTIMIZATION OF BIOGAS BASED POWER PRODUCTION:COMPREHENSIVE THERMOECONOMIC ANALYSIS AND EVALUATION METHODS

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DERYA HAYDARGİL

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by

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Derya HAYDARGİL

ABSTRACT

COST OPTIMIZATION OF BIOGAS BASED POWER PRODUCTION-COMPREHENSIVE THERMOECONOMIC ANALYSES AND EVALUATION METHODS

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In this thesis, the comprehensive thermoeconomic analysis and optimization approaches were applied to an existing biogas fuelled and internal combustion engine powered cogeneration system located in Gaziantep with an electrical power output of 1000 kW and a hot water mass flowrate of 20.9 kg/s.In the first part of the thesis, fuel and product cost analyzes of each component in the cogeneration system were carried out with four different thermoeconomic methods: Exergetic cost theory (ECT), modified productive structure analysis (MOPSA), wonergy and specific exergy costing method (SPECO). These methods are based on the developed thermoeconomic principles depending on the exergy. In actual operating conditions, the cost of electricity produced in the cogeneration system was calculated, according to the methods, respectively as $110.06/h (ECT), $85.54/h (MOPSA), $72.50/h (Wonergy) and $141.0/h (SPECO). It is concluded that ECT provides the most rational cost picture as the most detailed method in the context of mathematical analysis based on exergy. In the second part of the thesis, the biogas engine powered cogeneration system was examined using two different thermoeconomic optimization methods: Thermoeconomic functional analysis (TFA) and engineering functional analysis (EFA). Both methods take into consideration only the units in the exhaust gas line as of the functional structures in which they are developed. As a result of the analyses, the optimized thermoeconomic cost of electricity was calculated as $26.86/GJ with the TFA method and $24.40/GJ with the EFA method.
Keywords: Exergy analysis, Economics, Thermoeconomics, Biogas engine powered cogeneration, Optimization.

ÖZET

BİYOGAZ TABANLI GÜÇ ÜRETİMİNİN MALİYET OPTİMİZASYONU-KAPSAMLI TERMOEKONOMİK ANALİZLER VE DEĞERLENDİRME YÖNTEMLERİ

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Bu çalışmada, kapsamlı termoekonomik analiz ve optimizasyon yaklaşımları, Gaziantep'te bulunan, 1000 kW elektrik ve 20.9kg/s sıcak su çıktısı olan biyogaz yakıtlı ve içten yanmalı motor tahrikli gerçek bir kojenerasyon sistemine uygulanmıştır. Tezin ilk bölümünde kojenerasyon sistemindeki her birbileşenin yakıt ve ürün maliyet analizleri dört farklı termoekonomik yöntemle gerçekleştirilmiştir: Ekserjiye bağlı maliyet teorisi (ECT), değiştirilmiş üretken yapı analizi (MOPSA), wonergy ve özgül ekserjiye bağlı maliyet analizi (SPECO). Bu yöntemler ekserjiye bağlı olarak geliştirilmiş termoekonomik prensiplere dayanmaktadır. Gerçek çalışma şartlarında kojenerasyon sisteminde üretilen elektriğin ekserjiye bağlı maliyetleri, yöntemlere gore sırasıyla, 110.06 $/h (ECT), 85.54 $/h (MOPSA), 72.50 $/h (Wonergy) ve 141.0 $/h (SPECO) olarak hesaplanmıştır. Kojenerasyon sistemini ekserjiye dayalı matematiksel analiz bağlamında en detaylı inceleyen yöntem olarak ECT' nin en rasyonel maliyet tablosunu verdiği sonucuna ulaşılmıştır. Tezin ikinci bölümünde biyogaz motorlu kojenerasyon sistemi iki farklı termoekonomik optimizasyon yöntemi kullanarak incelenmiştir: Termoekonomik fonksiyonel analiz yöntemi (TFA) ve mühendislik fonksiyonel analiz yöntemi (EFA). Her iki yöntem de geliştirildikleri fonksiyonel yapılar itibarıyla sadece egzoz gazı hattındaki üniteleri dikkate almaktadır. Analizler neticesinde elektriğin en-iyileştirilmiş termoekonomik maliyeti TFA yöntemiyle 26.86 $/GJ, EFA yöntemiyle 24.40 $/GJ olarak hesaplanmıştır.

Anahtar kelimeler: Ekserji analizi, Ekonomi, Thermoekonomi, Biogaz beslemeli kojenerasyon, Optimizasyon.

''To my son, METEHAN''

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LIST OF SYMBOLS

Uppercase letters

C	Compressor
T	Turbine
EGHE	Exhaust Gas Heat Exchanger
HE	Heat Exchanger
LOHE	Lubrication Oil Heat Exchanger
P	Pump
GE	Gas Engine
A	Incidence matrix of a system,
$\mathrm{\dot{C}}$	Thermoeconomic cost of a flow, \$/h
$\dot{C}$	Thermoeconomic cost vector of a system, \$/h
$\mathrm{\dot{E}x}$	Flow exergy of, kW
$\dot{E}x$	Flow exergy vector, kW
$\mathrm{\dot{E}x}^*$	Exergetic cost, kW
$\dot{E}x^*$	Exergetic cost vector, kW
$\mathrm{\dot{E}x_F}$	Fuel exergy, kW
$\dot{E}x_F$	Fuel exergy vector, kW
$\mathrm{\dot{E}x_F^*}$	Fuel exergetic cost, kW
$\mathrm{\dot{E}x_P}$	Product exergy, kW
$\dot{E}x_P$	Product exergy vector, kW
$\mathrm{\dot{E}x_P^*}$	Product exergetic cost, kW
K	Wonergy, kW
ƙ	Wonergetic input ratio
R	Residue or lost, kW

Lowercase letters

c	Unit exergoeconomic cost, $/GJ
c^*	Unit thermoeconomic cost, $/GJ
c_T	Unit exergoeconomic cost of thermal exergy for gas streams, $/GJ
c_M	Unit exergoeconomic cost of mechanical exergy for gas streams, $/GJ
d_T	Unit exergoeconomic cost of thermal exergy for liquid streams, $/GJ
d_M	Unit exergoeconomic cost of mechanical exergy for liquid streams, $/GJ
i	Generic index associated to components
j	Generic index associated to flows
m	Number of flows of a system
n	Number of components of an installation

Subscripts

dest	Destruction
F	Fuel
i	Components
P	Product

Greek letters

κ	Exergetic unit consumption
κ^*	Exergetic unit cost
ε	Exergetic efficiency

CHAPTER 1

INTRODUCTION

1.1 Background

The focal point of energy debate is how future energy demands are met. Renewable energy sources and alternative energy such as waste to energy potentials in cities have been tought to play an important role in solving this problem. With the development of newer and more efficient technologies, the possibility of trust in renewable energy systems can be examined extensively. Furthermore many countries are restructuring their energy industries and requiring more competition into energy markets. Restructuring can give the opportunity to use renewable resources by facilitating the assessment of distributed resources because it goals to decentralize decision-making [1].

In addition, financial, environmental or other constraints will occur in the conversion of existing capacities of electricity companies into non-oil fuels or in the construction of new alternate-fuelled capacity. A variety of alternative fuels and conversion technologies are being tested for the industrial, commercial and electrical service sectors. One of the most promising commercially available technologies may be cogeneration. Cogeneration systems generate both electrical (or mechanical) energy and thermal energy from the same primary energy source [2].

Careful examination of cogeneration or any power producing system generating has many benefits. The first one is the most efficient use of resources used as fuel. The other is the profit to be obtained economically. In this context, thermoeconomics is a combination of physics and energy developed to study power plants. Thermoeconomics primarily analyzes the system thermodynamically, and the key point is exergy. It then allows cost analysis by combining the exergy with the money spent for the installation of the system. Of course, during these processes, identifying and simulating the components in the system correctly will enable us to get the most reliable results.

The purpose of this study is to deeply comprehend the cost structure of power generation systems by applying the thermoeconomic cost analysis methods based on exergy, by applying the algorithms of thermoeconomic cost analysis methods based on detailed mathematical foundations to all sub-components of an existing cogeneration system which consumes a renewable energy source (biogas) and thus comparing the advantages and disadvantages of all methods in practice. Also, the optimization of the cogeneration system is performed from different thermoeconomic perspectives and the obtained results are compared. This study may be a guide for the improvement of the cogeneration systems to set light on the complex problems based on cost flow.

1.2 Scope and Outline of The Study

In Chapter 2, a comprehensive literature survey on the history of thermoeconomics from how this idea came into being is performed. Literature survey is performed under four titles; brief history of thermoeconomics, exergy based cost accunting methods, exergy based optimization methods and exergetic and/or economic analyses of biogas based power production.

In Chapter 3, the detailed description of GASKI Biogas Engine Powered Cogeneration System including main and auxiliary system components is presented.

In Chapter 4, the theoretical background of thermoeconomic cost analysis methods based on exergy is presented in detail. The mathematical background, on which each method is based, is elaborated by providing the main and auxiliary equations developed according to the sub-components of the heat and power generating systems.

In Chapter 5, general principles and formulations of thermoeconomic optimization methods are presented. These methods provide a primary optimization performance measure which is minimizing the total levelized cost of the system products that includes the cost of external fuel resources, capital investment and operating and maintenance cost.

In Chapter 6, the main and auxiliary equations and optimization methods developed in the context of the thermoeconomic cost analysis theories based on exergy are applied to the sub-components of an existing biogas engine powered cogeneration system. Exergetic cost rate balances and corresponding auxiliary equations are formulated for each subsystem of the plant and the results are presented and discussed using the actual operating data obtained from the system.

In Chapter 7, our conclusions drawn from the study are pointed out and certain recommendations are improved.

CHAPTER 2

LITERATURE SURVEY

2.1 Introduction

The efficient use of energy and rational energy management have been seen as important research areas since the beginning of the last century. In this context, there are a number of qualified scientific initiatives aimed at improving the design and operation of energy systems, preventing energy production from harming the environment, and creating new disciplines.

Thermoeconomics or exergoeconomics, in its broadest sense, is a sophisticated science that combines heat transfer, fluid mechanics and economics [3] with the comprehensive analysis and assessment methods based on the second law of thermodynamics.

Its history explains why it is very closely related with second law analysis and the improvement of the concept of exergy. The first use of the term available energy is presented by Maxwell [4] in 1871 and Gibbs [5] was the first to provide an analytical basis for determining the available energy in a given situation. However his comments on the subject was very difficult and Keenan presented Gibbs results in simple and more practical terms. He published a paper about second law on costing purposes in 1932 [6] . He didn't perform exergy costing however he referred to it as the sharing of the cost associated with the cogeneration of electric power and steam. Keenan remarked that steam and the electricity values were supported in the "availability" not in their energy.

The name “exergy” was suggested by Rant [7] defined as external useful work in opposition to the energy (internal work). Benedict [8] introduced the idea of coupling exergy and cost streams firstly in 1948. He specified the total cost was addicted on the irreversibilities of an air separation plant and this cost was used for optimal design. The early work by Keenan and Benedict was widened by their students, especially Gyftopoulos [9]. Furthermore, a detailed report on exergy and its useage areas combining four paper was prepared by Wall [10].

The interaction between cost and efficiency was emphasized by Tribus and Evans [11] in the early 1960’s. They did exergy analysis on a project which canalized them to the idea of exergy costing and its applications to engineering economics, for which they coined the word “thermoeconomics”. The essence of the Evans-Tribus procedure depends on tracing the flow of money, fuel cost and operation and amortized capital cost in a plant, also regards each stream with its exergy. Also Evans [12] did his Msc. thesis on the contribution theory of thermoeconomics. El-Sayed connected with Evans and Tribus, then their paper [13] was published in 1970. The mathematical foundation for thermal system optimization is given in this study. They improved a specific strategy [14] for the process economics through thermoeconomic analysis.

Obert and Gaggioli [15,16] worked in the optimal design of power plant steam piping. They suggested costing the steam exergy at a value to that of power produced, preventing irreversibilities for electricity so they didn’t emerge. Gaggioli directed the Ph.D theses of Reistad [17] and Wepfer [18] on second law costing methods, that contain the definition of rules to ensure a rational distribution of the cost. Gaggioli and Wepfer [19,20] studied on cost accounting applications and the composition of thermoeconomic flow diagrams.

Tsatsanoris and Winhold [21] prepared a report about concept of exergy and the general methodology of the exergetic analysis and thermoeconomic analysis of energy conversion systems in 1984. Thabit et. al [22] applied the thermoeconomic analysis on a combined heat and power plant. The interest and works regarding to thermoeconomic analysis highly increased when Tsatsaronis introduces the key concept of fuel and product in 1985.

Kotas [23] implicated some works including thermoeconomic analysis in 1985 in the book, “The exergy method of thermal plant analysis”, which is one of the most important references in exergy analysis and thermoeconomics.

Application of thermoeconomic analysis in the optimization and design of thermal systems became popular in the 1990s. Tsatsanoris [24] discussed the combination of exergy with conventional concepts from engineering economics to analyze and optimize the design and performance of energy systems.

CGAM project [25] which formed by Frangopoulos, Tsatsaronis, Valero and Von Spakovsky presented how the methodologies of each group of research could be applied by solving a predefined and simple problem of optimization of gas turbine cycle.

Tsatsaronis et. al [26] performed exergoeconomic evaluation and optimization of the CGAM problem with various exergy costing approaches, the exergoeconomic variables, and the procedures used in evaluating and optimizing energy systems. Tsatsaronis [27] also studied on design optimization using exergoeconomics on complex energy systems.

Bejan et. al [28] published a book which focused on the methods of exergy analysis, entropy generation minimization, and thermoeconomics in an evolutionary manner.

At the beginnings of 2000s another project called TADEUS [29] was presented. Its aim was the application of procedures from different research groups in thermoeconomic analysis to the diagnosis of the energy system malfunction and inefficiencies. Establishment of the common concepts and nomenclature also comparing the results and also highlighting the main characteristics of each approach were the objective of this new effort.

Ayres [30] and Warr [31] stressed on the importance of exergy as a determinant of economic output, they supported this idea by examining the backward 100-year economy of key countries in the world. Ruth [32] decided that, attempts to quantify material and energy use from a thermodynamic perspective contribute usefully to the ongoing sustainability debate. Bryant [33] investigated a thermodynamic theory of economics, with several papers, containing emprical research, on monetary economics, peak oil and climate change. Bryant also wrote a book [34] which emphasized energy, resources, economy further on thermoeconomics and sustainability.

Sciubba et al., [35] presented a brief commented history of exergy and thermoeconomics from the beginnings to 2004. This work was guided the scientists who dealed with theoretical research, industrial development, and societal applications of exergetic concepts.

Querol et al., [36] indicated a practical approach to exergy and thermoeconomic analyses of industrial processes in a book. Exergetic cost and thermoeconomic costs are described in detail.

Thermoeconomic methods are investigated in two groups, based on cost accounting, and optimization techniques**.** Cost accounting methods are useful to determine the actual cost of products and provide a rational basis for pricing, while optimization methods are applied to find optimum design or operating conditions. In the next sections examples for cost accounting and optimization methods will be examined.

2.2. Exergy Based Cost Accounting Methods

Valero et al., [37] resumed two studies about the theoretical background supporting the main ideas of the exergy cost accounting and the thermoeconomic approach. Part I presented the basic requirements, with a simple example accompanying the dissertations, to determine the exergy and thermoeconomic costs and to perform the thermoeconomic analysis of a complex system. The connections with other thermoeconomic approaches were briefly explained.

Valero et al., [38] developed the mathematical formulations of three applications of the thermoeconomic analysis methodology described in Part I of the paper: the operation diagnosis study, including new concepts that helps to separate different contributions to those inefficiencies; the local optimization process in case of special conditions for the whole plant, and the benefit maximization (a direct application of the exergy costs accounting analysis). The operation diagnosis, which is the most complex and sophisticated application, was showed with the help of an example: the cogeneration plant, as it was described in Part I.

2.2.1 Exergetic Cost Theory (ECT)

Valero et al., [39] defined an incidence matrix which represents a system and interconnects the subsystems with flows in this system. Incidence matrix helps to determine the exergetic costs through the system. They concluded that this matrix was uniqueness because there was no uncertainty in obtaining it although there were alternatives which lead, in the absence of external assesments and at the minimum aggregation level, to the natural exergetic cost, and with the external assesments and at the maximum aggregation level, to the final exergetic cost of the products.

Valero et al., [40] used the basic idea of exergetic cost theoretically to obtain a method for determining the thermoeconomic cost. This method was put on the clarifying ideas on fuel-product representation and showed the superstructure of the thermodynamics-economics interaction. The two main routes for calculating costs were identified and criticized in the light of the cost hexagon method.

Valero et al., [41] analyzed a simple cogeneration plant in a sugar factory using a method which constructed a cost structure matrix as a union of the physical and productures of the system. This method was based on the thermoeconomic costs using the theory of exergetic cost.

Valero et al., [42] presented the theory of perturbations, which was an offspring of the exergetic cost theory. For a given energy system composed of subsystems interconnected by flows of energy, a perturbation of the second law efficiency of any subsystem affects the production of the rest of the components, finally causing an increase of the resources consumption of the whole plant at constant total production. It could be said that, a small malfunction of a subsystem (degradation of its efficiency) caused dysfunctions of the rest of the components (variation of its production without changing its efficiency).This study emphasized how to compute automatically on one hand, the reflections of these malfunctions in the increase of resource consumption, and on the other hand the dysfunctions emerging from any mulfunction of any subsystem in any energy structure.

Lozano et al., [43] applied exergetic cost theory on a three component power producing system. Both exergetic and exergoeconomic costs were determined according to the methodology principles. Furthermore they studied on a cogenneration plant in the aspects of operation optimization, local optimization and energy audit of the performance test.

Valero et al., [44] presented an optimization strategy for complex thermal systems. The strategy was based on conventional techniques and incorporates assumptions and consequences of the exergetic cost theory and of symbolic exergoeconomics. In addition to the results obtained by conventional techniques, this method provided valuable information about the interaction of components.

Vieira et al., [45] made an analysis of a thermal power plant with the primary objectives of knowing its actual operating condition and evaluating the costs of internal flows. The exergetic cost theory was the basic tool for this analysis. Once the preparatory steps were taken, the exergetic and thermoeconomic analyses of the plant were performed. These analyses allowed the identification of the main plant inefficiency sources as well as the exergetic and economic costs of every internal flow of the plant.

Zhang et al., [46] applied exergy cost analysis based on structural theory of thermoeconomics to a 300MW pulverized coal fired power plant located in Yiyang (Hunan Province, China). To derive the thermoeconomic analysis of the plant, a simulator was developed from thermodynamic modeling of the plant. Three thermoeconomic variables were described for improving the exergy cost equations in the structural theory of thermoeconomics. Several simulation cases had been examined in detail using the improved exergy cost method.

Deng et al., [47] provided an exergy cost analysis method based on the structural theory of thermoeconomics to a gas fired microtrigeneration system, which used a small-scale generator set driven by a gas engine and a new small-scale adsorption chiller. The thermoeconomic model for the system based on the fuel–product concept was defined to quantify the productive interaction between various components. The distribution of the resources and costs of all flows in the productive structure were calculated by solving a set of equations according to the experimental data. By adopting the exergy cost analysis method, the production performance of components at design and variable conditions of combined cooling and power were evaluated in detail. Moreover, a comparison between the method of conventional exergy analysis and exergy cost analysis was presented.

The previous exergetic cost theory works provided a method to analyze the cost formation process, based on computing the production costs as the sum of the irreversibilities of the processes required to obtain a product. Torres et al., [48] showed how to decompose the production cost into its unavoidable and avoidable parts. By means of this fact it was possible to determine which part of the cost could not be decreased because of technological and thermodynamic limitations, which part of the cost caused from the investment costs of the system or due to the formation and abatement cost of the residues and finally which part was reasoned by the avoidable irreversibilities of the own component and how much they subscribed to the cost of the rest of components.

A more complete analysis for residues cost allocation had been performed by Torres et al. [49]; they presented the mathematical basis for the cost assessment and the formation process of residues. In order to perform this, they extended the exergetic cost theory cost propositions to include a new concept: the cost of the residues generated by a productive component, and developed, the equations provided by symbolic exergoeconomics to include the cost formation process of residues.

Orozco et al., [50] proposed the thermoeconomic diagnosis, as a part of the exergy cost theory, of thermal systems for power generation aiming the identification of the elements of the cycle (gas turbines, steam turbines, heat exchangers, etc.) with an abnormal behavior and consequently causing fuel over-consumption for the same level of power production. Also they presented an analysis of a combined cycle to identify and quantify the avoidable exergy destruction, and how this type of exergy was affected by the presence of malfunctions associated with each equipment and malfunctions induced by the other components of the cycle.

2.2.2 Modified Productive Structure Analysis (MOPSA)

Kwak et. al., [51] applied MOPSA method to a 500 MW combined cycle plant to estimate the unit costs of electricity produced from gas and steam turbines. The exergy losses due to heat transfer and their corresponding cost losses for non-adiabatic component were taken into account for perfect exergy and cost balances of components as well as of the overall system. Possible configurations from the combined cycle plant, such as gas turbine and gas-turbine cogeneration systems were compared by detailed analyses.

Kwak et al., [52] investigated the cost structure of the CGAM system by using MOPSA. An emphasis put on how the cost structure of the system was influenced by the chosen level of aggregation that specifies the subsystems. It had been detected that the unit cost of products was dependent on the chosen level of aggregation of the system only when one considered the entropy flow as one of the parameters to determine the unit cost of products.

Bandpy et al., [53] performed exergetic and thermoeconomic analyses of 117 MW gas turbine plant in Mahshahr, Iran. The production costs were obtained from SPECO, MOPSA and Moran methods. The production costs estimated from the three methods of exergoeconomics analyses were compared. They decided according to the results that the MOPSA method was the best method for estimate the unit cost of electricity produced from gas turbines.

Keçebaş [54] performed MOPSA analysis of Afyon geothermal district heating system (GDHS) located in the city of Afyonkarahisar, Turkey. In this analyses, mass and energy conservation laws were applied to each component of the system. Quantitative balances of the exergy and exergetic cost for the whole system and its each component was carefully thought. The results stated that about 52.49% of the input cost of the Afyon GDHS was lost from the heat exchangers, 16.26% from pipes, and 7.22% from pumps.

2.2.3 Wonergy Method

Kim [55] proposed a new thermoeconomic methodology for energy systems in the fields of cost allocation, cost optimization, and cost analysis. The proposed methodology was very simple and clear. That's, the number of the proposed equation was only one in each field, and it was developed with a wonergy newly introduced in his study. The wonergy was defined as an energy that can equally evaluate the worth of each product. Any energy, including enthalpy or exergy, can be applied to the wonergy and be expressed by this equation. In order to confirm its validity, the CGAM problem and various cogenerations were investigated. Seven sorts of energy, including enthalpy and exergy, were applied for cost allocation. Enthalpy, exergy, and profit were applied for cost optimization. Enthalpy and exergy were applied for cost analysis. He concluded that various forms of wonergy could be applied to the analysis of thermoeconomics.

2.2.4 Specific Exergy Costing/Average Cost (SPECO/AVCO) Approach

Mothci et al., [56] presented the implementation of an integrated approach to perform mathematical exergoeconomic optimization of thermal systems based on genetic operators. For costing purposes, the methodology SPECO/AVCO was adopted.

Lazzaretto et al., [57] proposed a systematic and general methodology to define and calculate exergetic efficiencies and exergy related costs in thermal systems. The methodology based on SPECO in which the fuel and product of a component were defined by taking a systematic record of all exergy additions to and removals from all the exergy streams of the system. They determined the costs by implementing basic principles from business administration. Cost equations were represented in a general matrix form.

Abuşuğlu et al., [58] studied on the exergetic and thermoeconomic analysis of diesel engine powered cogeneration systems. The exergoeconomic analysis was based on SPECO and it was determined that the specific unit exergetic cost of the power produced by the plant is 10.3 $/GJ.

Ballı et al., [59] applied SPECO to an actual trigeneration system with a rated output of 6.5 MW gas–diesel engine installed in the Eskisehir Industry Estate Zone, Turkey. Energy and exergy efficiencies, equivalent electrical efficiency, the Public Utility Regulatory Policies Act efficiency, fuel energy saving ratio, fuel exergy saving ratio and other thermodynamic performance parameters were obtained for the trigeneration system. The efficiencies of energy, exergy, the Public Utility Regulatory Policies Act efficiency and equivalent electrical efficiency of the entire system were determined as 58.97%, 36.13%, 45.7% and 48.53%, respectively.

Yıldırım et al., [60] considered the thermoeconomic analysis in order to provide cost based information and suggested possible locations for a diesel engine combined heat and power (CHP) system which had a total installed electricity and steam generation capacities of 11.52 MW and 9.0 tons/h at 140 °C respectively. According to SPECO results, the specific unit exergy cost of electrical power produced by the CHP system is calculated as 4.48 $/GJ.

Abuşuğlu et al., [61] represented the thermoeconomic analysis of a biogas engine powered cogeneration system. They applied SPECO method to characterize the operation of an existing cogeneration system in detail and a methodology based on exergoeconomic relations and is applied to share out cost flows through subcomponents of the plant.

Lazzaretto [62] focused on some specific components through a system, in which there might be uncertainties in the definition of fuel and product and in the consequent auxiliary cost equations, and tried to remove this uncertainties by comparing the results of the application of the SPECO method with a possible alternative approach under changes of the component behavior.

Durmuşoğlu et al., [63] analyzed a regenerative and irreversible closed cycle gas turbine power plant with pressure and optimized according to exergoeconomic performance criterion. The exergoeconomic function for optimization was determined as exergy of net power output of the facility per unit total exergy costs. The unit total exergy costs had been combined with investment cost of components, fuel exergetic cost, environmental exergetic cost, exergy destruction cost and stream line exergetic costs. The cost equations had been performed according to a SPECO/ AVCO method.

Mohammadkhani et al., [64] presented exergetic and exergoeconomic analysis of a diesel engine based CHP system that produced 277 kW of electricity and 282 kW of heat. The CHP system was first thermodynamically analyzed through energy and exergy. Then cost balances and auxiliary equations were applied to subsystems, hence, cost formation in the plant was obtained using SPECO. Finally a parametric study was used to show effect of ambient temperature on important energy, exergy and exergoeconomic parameters of the CHP system.

Khaljani et al., [65] did thermodynamic, exergoeconomic and environmental assessment of a cogeneration of heat and power cycle, considering the three objective functions of first and second law efficiencies and the total cost rates of the system.

The proposed combined heat and power cycle included a gas turbine and an organic rankine cycle through a single-pressure heat recovery steam generator. In order to assess the effects of design parameters on the objective functions, a parametric study was conducted.

2.2.5 Last-in-First-Out (LIFO) Approach

This approach was developed by Tsatsaronis et al. [66]. LIFO principle of cost accounting was used for the spent exergy units to calculate the cost of exergy supply to the carrier. The method did not need auxiliary assumptions in the exergoeconomic analysis of energy systems and improved the fairness of the costing process. This approach was supported by a simple idea, which is directly linked between asset management and valuation method. The exergy units that were supplied last to the material stream are used first. Thus, it was simple to calculate the cost associated with the exergy units removed from a material stream in a process step provided that this cost was calculated in the previous steps during which the exergy units currently removed from the stream are then supplied to it.

Structural theory of thermoeconomics was suggested as a standard and common mathematical formulation for all thermoeconomic methodologies employing thermoeconomic models that could be expressed by linear equations. Erlach et al., [67] applied the LIFO and the structural theory to a combined cycle plant and it was shown that the equation systems obtained from both methods were the same. Moreover, a procedure to develop the productive structure representing the thermoeconomic model of LIFO (i.e. from which the same costing equations were obtained as with the LIFO approach) was explained in detail, which provided the tools to reproduce the costs obtained from LIFO with the structural theory for complex energy systems.

2.3 Exergy Based Optimization Methods

Torres et al., [68] aimed to achieve a better understanding of the thermoeconomic theory of system optimization and the structural theory [69], which is a general mathematical formulation based on linear models, of cost in order to unify and take advantage of both theories in his Ph.D. thesis.

Vieira et al., [70] presented the development and implementation of an integrated approach for mathematical exergoeconomic optimization of complex thermal systems. By exploiting the computational power of a professional process simulator, the suggested integrated approach gave permission for the optimization routine to ignore the variables associated with the thermodynamic balance equations and thus deal only with the decision variables. It was applied to a complex cogeneration system, which included all the major components of a typical thermal plant, and requested more than 800 variables for its simulation.

Of course, there are a lot of publications related to optimization in the literature other than the above two studies, but this thesis will focus on two optimization theories in particular. These theorems will be given in next sections.

2.3.1. Thermoeconomic Functional Approach (TFA)

This approach was first studied as a Ph.D. thesis by Frangopoulos [71,72] while the first remarkable application of it was the CGAM problem.

Von Spakovsky et al., [73] discussed TFA on a rankine reheat cycle with regeneration. Functional digram of the system was presented. In order to analyze this diagram its corresponding set of thermodynamic and cost equations, the relationship of the cycle's thermodynamic states to the cost flow rates of exergy and negentropy were determined. Lagrange method applied to reach the results.

Agazzani et al., [74] demonstrated the capability of an original modular simulator tool for the thermoeconomic analysis of thermal energy systems. The approach employed was based on the TFA which, through definition of the functional productive diagram and the establishment of the capital cost function of each component, allowed the marginal costs and the unit product costs, i.e., the internal economy, of the functional energy flows to be obtained in correspondence to the optimum point. The optimum design of the system was obtained utilizing a traditional optimization technique, which included both physical structure of the energy system described in terms of thermodynamic variables and cost model. As an application example to show the practicability of the tool, the thermoeconomic analysis of various complex multipressure combined cycles (with or without steam reheating) was studied.

Frangopoulos [75], stressed that TFA was a design optimization method and presented it on the functional diagram concept and assigned only one function and one product to each unit so that auxiliary equations were not needed in the solution procedure. Lagrangian method of mathematical optimization was the basis of this methodology.

Frangopoulos [76], indicated an application example of design optimization. A cogeneration system, which operated on natural gas and produces electricity and heat in the form of saturated steam was used. Firstly, the system was thermodynamically and economically modeled. After drawing functional diagram, a cost balance was written for each unit considering a break-even operation. Optimization problem was stated with independent variables and solved with the help of Lagrangian multipliers.

Galanti et al., [77] carried out on the micro gas turbines in the range 25–500 kWe. The investigation had been pursued using WTEMP code (Web-based ThermoEconomic Modular Program), developed by the thermochemical power group of the university of Genoa. TFA was performed on the basis of the thermodynamic, geometric and capital cost parameters of the main micro gas turbine devices.

2.3.2. Engineering Functional Approach (EFA)

von Spakovsky et al., [78] emphasized the essential building blocks of a new formalism called Engineering Functional Approach. Higher degrees of decentralization for engineering system optimization were resulted from this formalism. This result was important since it ensured a more stable economic environment for individual components which permitted more rapid synthesis and greater system improvement. The general nonlinear programming problem was used because of its concise treatment of optimization.

von Spakovsky et al., [79] discussed symmetric engineering decomposition and subsequent decentralization of engineering systems. They concluded that the method of Lagrange multipliers was a good way to proceed with the large decomposition of large engineering optimization problems.

von Spakovsky [80] performed a comprehensive study to optimize CGAM problem on the principles of EFA. The internal economy of EFA was stressed. He discussed the modeling and solution philosophies of the system. He performed modular approach, Lagrangian approach and decomposition approach, last of all they nearly gave the same results.

2.4 Thermoeconomic Analyses of Biogas Based Power and Heat Production

Damrongsak et al., [81] examined a compact modular refrigeration system driven by small biogas engine. Investigation of the module performance is performed in terms of cooling capacity, primary energy ratio, thermal efficiency and fuel consumption. The experimental results indicated that a range of the desired refrigerating capacity of the compact module can be achieved by means of varying engine speed.

Lian et al., [82] implemented a methodology, based on the second law of exergy, to evaluate the thermoeconomic potential of a trigeneration plant employing biomass as its energy source. Four different plant configurations to generate varying degrees of heat, electricity and/or cooling were defined and their cost effectiveness was stated with varying economic and operating parameters.

Kang et al., [83] evaluated the economic feasibility of small combined heat and power and combined cycle systems using a 5 MW-class gas turbine fuelled with biogas. They used practical hourly and seasonal variations of the combined heat and power and combined cycle performance based on detailed performance analysis. Also, economic indices such as the annual gross margin, the net present value of the cash flow and the payback period were predicted by using the investment and running costs of the entire facilities and the prices of electricity and heat.

Basrawi et al., [84] made a study which compare biogas fuelled micro gas turbine cogeneration systems with various output powers in different scales of sewage treatment plants under various ambient temperature conditions and they obtained some results for optimization.

Carolino et al., [85] studied the first and second law analyses of a cogeneration system, which produced electrical and thermal energies, run with the biogas produced in a landfill. The objectives were to identify locations where major irreversibilities occur, to evaluate their magnitudes, and to assess the energy and exergy efficiencies of the global system and of its constituent units. The results indicated that the overall plant first law efficiency is 37.9% and the exergy efficiency is 36.2%, which was far from the thermodynamic ideal limit. The internal combustion engine and one of the radiators were the most inefficient units, as judged by the parameters degree of thermodynamic perfection and exergy destruction quotient.

Rubio-Romero et al., [86] aims to identify and analyze the economic viability, net present value, internal return rate, payback and profitability of return on investment of the potential biogas cogeneration from the municipal solid waste of all the landfills in Andalusia.

Soltani et al., [87] demonstrated the application of gasification for electricity production was investigated via energy, exergy and exergoeconomic analyses for two configurations: (1) externally fired biomass combined cycle, and (2) combined cycle with co-firing of biomass and natural gas. The second configuration was determined to be more economic (on a large scale) as its relative cost difference and exergoeconomic factor were less than those for the first configuration. It was emphasized that the energy and exergy efficiencies of combined cycle with co-firing could be about 2% and 4% higher than those of the externally fired combined cycle, respectively.

Xydis et al., [88] analyzed the electricity production exergetically from a landfill in the area of Volos, Greece and discussed how the extension of the landfill influences electricity production, something not studied so far. The electricity production potential was analyzed for every extension phase and comparative results were presented.

Siefert et al., [89] presented an exergy and an economic analysis of a power plant that uses biogas produced from a thermophilic anaerobic digester (AD) to fuel a solid oxide fuel cell (SOFC). They performed a 4-variable parametric analysis of the AD-SOFC system in order to determine the optimal design operation conditions depending on the objective function of interest. Results were showed on the exergy efficiency (%), power normalized capital cost ($\$kW^{-1}$), and the internal rate of return on investment, IRR, ($\% \, yr^{-1}$) as a function of the current density, the stack pressure, the fuel utilization, and the total air stoichiometric ratio.

Yingjian et al., [90] presented an example of the energy balance and the efficiency analysis for power generation in internal combustion engine sets using biogas. How to improve the energy efficiency of biogas processed was discussed, for example, the biogas purification (removal of CO_2 and H_2S) to enrich methane in biogas could be used for the power fuel, meanwhile, it enhances the efficiency of power generation. A combined heat and power efficiency of over 80% can be achieved if heat of both the exhaust gas and water heated within the cylinder jacket is utilized.

Somehsaraei et al., [91] investigated the fuel flexibility of the existing micro gas turbines (MGT) in biogas application and analyze the impact on the engine performance of burning biogas instead of natural gas. A steady state thermodynamic model was improved and confirmed in design and off-design cases. Using the confirmed model, the impact of biogas with various compositions (i.e. with reduced methane fraction) on the MGT performance was examined over the full range of operational conditions varied by changes in either power load demand or ambient temperatures. The results showed a wide-ranging assessment of the performance of an MGT fed with biogas as a low heating value fuel, illuminating the viability of the MGT for use in biogas application, with slightly negative effect on the engine performance, compared to the reference case, i.e. natural gas. The use of MGT systems for small-scale biogas plants were motivated, to reduce the dependency on fossil fuels and greenhouse gas emissions.

The influence of firing biogas on the performance and operating characteristics of gas turbines was investigated by Kang et al. [92]. They simulated combined heat and power systems based on two different gas turbines (simple and recuperative cycle engines) in a similar power class. A wide range of biogas compositions differing in CH_4 content was tested. It was observed that gas turbine efficiency increased with decreasing CH_4 content in the simple cycle engine, but decreased in the recuperative cycle engine.

Cao et al., [93] investigated a biomass fired Kalina cycle with a regenerative heater which is generally utilized to heat the feedwater and to increase the efficiency in coal fired steam power plant. The mathematical model of the biomass fired Kalina cycle with a regenerative heater was built to conduct numerical simulation. A parametric analysis was examined the effects of some key thermodynamic parameters on the system performance. Additionally, a parametric optimization was performed by genetic algorithm to obtain the optimum performance of system.The results indicated that there exists an optimum extraction pressure and its corresponding maximum fraction of flow extracted from turbine to maximize the net power output and system efficiency.

Li et al., [94] analyzed a full-scale biogas plant in a rice–wine–pig system in Zhefang winery in China. They presented an assessment of the application of biogas fermentation in Zhefang winery, providing information about potential profitability and economic impacts. For this purpose, the mass flow and energy balance in the biogas plant were emphasized. The potential energy generated and consumed through biogas were analyzed. Furthermore, an economic analysis was provided to account for the introduction of the anaerobic digestion plant in the ecosystem.

Wang et al., [95] analyzed a combined cooling heating and power system based on biomass gasification by integration with a heat exchanger to recover waste heat from the high-temperature product gas for effective utilization in different operating conditions. The exergy efficiencies and the exergy destructions in the cooling and heating modes were identified. Next, the unit exergy-based cost of products was calculated, and the cost allocation was presented using the specific exergy costing approach, including electricity, water for cooling or heating, and domestic hot water. A sensitivity analysis is emphasized to obtain the unit exergy cost of the products along with the influence factors, such as biomass cost, investment capital, interest rate, service life and operating time. Finally, the selling price coefficient of the product cost was obtained to recover the installation cost.

Yasar et al., [96] performed waste to energy analysis of a large scale sugar industry. Biogas power plant of Shakarganj sugar mills is generating its own electricity from biogas produced by the waste (spent wash). The biogas was passed through desulphurization and dehumidification units to remove the sulphur content. The total electricity production was 37.7 million kWh and the total steam (28260 t) generated was used by the mill. The electricity production efficiency by using new biogas boilers was 92%. The estimated CO_2 emission reduction during the year was 28032 tCO_2 e.

Mehr et al., [97] proposed four different configurations of natural gas and biogas fed solid oxide fuel cell and analyzed thermoeconomically focusing on the influence of anode and/or cathode gas recycling.

Shariatzadeh et al., [98] modelled and optimised SOFC for the trigeneration hybrid system fed by biogas produced from hospital waste. They studied a 50 kW tubular SOFC combined with a chiller, heat recovery steam generator, combustion chamber and required equipment. The system ensured 50% of total electricity required using the produced biogas and also provided the whole cooling load of the hospital using an absorption chiller. Further, an economic optimisation was studied. The aim was to give a comprehensive perspective on the affordability of using the proposed system by considering economic parameters along with thermodynamic principles. The single-objective optimization was performed by genetic algorithm. The results showed that under the acquired optimum conditions, the proposed system can be economically affordable in long term.

Uson et al., [99] presented a thermoecological evaluation of a trigeneration module based on an internal combustion engine fuelled with selected fuels of various origin: domestic/mixed-origin natural gas, coal mine methane and biogas. The generated products contained; electric energy, heat available in hot water and cold generated in an absorption chiller. Transformations of energy and exergy in the trigeneration module were analysed, and the TEC (thermoecological cost) of the products were obtained. The decomposition of TEC into the cost of resources, the contribution of process irreversibility and the equivalent cost of noxious substances were presented. It was indicated how the TEC of final products depent on the chosen resource, on the process irreversibility, and on the waste contribution. TEC of electricity produced in the trigeneration module varies from 0.30 (biomass syngas) to 3.11 (mixed origin natural gas), and the TEC of the generated heat and cold varies from 0.61 to 6.46 (heat) and 3.37 and 35.5 (cold) accordingly.

Sigarchian et al., [100] proposed a hybrid power system consisting of photovoltaics panels, a wind turbine and a biogas engine to supply the electricity demand of a village in Kenya. The feasibility of using locally produced biogas to drive a backup engine in comparison to using a diesel engine as backup was researched through a technoeconomic analysis using hybrid optimization model for electric renewables.

This hybrid system was also compared with a single diesel based power system. The results indicated that the hybrid system integrated with the biogas engine as backup can be a better solution than using a diesel engine as backup. Regarding CO_2 emissions, using a biogas engine as backup saves 17 tons of CO_2 per year compared to using the diesel engine as backup.

Santos et al., [101] aimed to show how the biogas biomethanisation from primary and secondary treatment of activated sludge from a wastewater treatment plant, could be an alternative renewable energy option from fossil fuels, which offered competitive advantages and points out new horizons for the use of this fuel. This study analyzed the biogas combustion and energy recovery processes from a thermodynamic, thermoeconomic and exergetic point of view. The results indicated that the boiler of the process is the main source of irreversibility and exergy destruction. Besides, the energy and exergy economic value of exhaust gases from the combustion chamber were significant and worthwhile to be exploited. For this reason, the present study explored the applicability and suitability of integrating a Stirling engine in such process. The study displayed that it was possible to create a small micro cogeneration system which lead to sustainable waste management and energy savings in the treatment plant itself.

Ozdil et al., [102] presented a detailed exergy and exergoeconomic analyses of a biogas engine powered electricity production system in a wastewater treatment plant located in Adana, Turkey. The effect of the each system component on the exergy efficiency and exergoeconomic parameters was analyzed seperately. The analysis indicates that major exergy destruction happens in the gas engine.

Barzegaravval et. al, [103] conducted exergoeconomic assessment of a biogas based gas turbine system with preheater. Effects of fuel composition on the exergetic and economic performance of a plant were studied, and comparison between two fuel pricing methods had been carried out. Two definitions for fuel pricing were used, one based on the exergy and the other based on the lower heating value of the biogas and the results were compared. In addition, the cost factors were defined and the cost of generated power were evaluated. To add more generality to the work, system sizes ranged from 1 to 10 MW was taken into consideration to understand the effect of system size as well. Results revealed that fuel pricing based on the exergy gives more realistic evaluations. Furthermore, when methane content is changed from 0.95 to 0.6, total cost rate of the plant rised around 1% and electricity cost augments. Exergetic efficiency mitigated when methane content is reduced.

Gholizadeh et al, [104] carried out feasibility investigation of a modified organic Rankine cycle coupled with a gas turbine cycle fueled by biogas (60% methane , 40% carbon dioxide) as a heat source. Thermodynamic and thermoeconomic analysis were employed as the most powerful tools to estimate performance and cost of the system and the results are compared with the basis coupled system. Also, to investigate how the proposed systems performed under any external disturbances, a thorough sensitivity study around the basic operating input parameters was carried out.

2.5 Conclusions

The extended overview provided in this chapter indicates that there are a few number studies on the comparative thermoeconomic analysis and optimization of cogeneration systems in literature. A good fraction of these studies considers CGAM problem when evaluating and comparing different methods. Some studies consider conceptual cogeneration designs with alternative systems and assumed operating conditions. This thesis differs from the previously conducted studies as follows:

a) The presented study is on the application of different comprehensive thermoeconomic approaches and optimization methods of biogas engine powered cogeneration systems. The thesis is original in this scope and content and there is no such study in the open literature, to the best of the author's knowledge and it is the main motivation behind this study.

b) In literature, a small number of studies consider biogas engine powered cogeneration systems and the analysis in these studies are mostly limited to conventional energy analysis and economic considerations and SPECO method.

c) The thesis provides theoretical foundation including procedure and formulation for thermoeconomic approaches and optimization methods of biogas engine powered cogeneration as well as applications on an actual system.

CHAPTER 3

BIOGAS POWERED COGENERATION SYSTEM

3.1 Introduction

Cogeneration is the definition of the combined generation of electric (or mechanical) and thermal energy from the same energy source [105]. The conventional way of meeting power and heat loads of one or more consumer is to purchase power from the national network and burning fuel (in a boiler or furnace) to produce heat. On the other hand, cogeneration or combined heat and power application is significantly reducing the total fuel consumption.

Large portions of heat are rejected to the environment either through the cooling circuits (steam condensers, cooling towers, diesel engine radiators etc.) or through the exhaust gases (gas turbines, diesel engines, Otto engines etc.) during the process of a conventional thermal power plant. The largest amount of this heat can be utilized and recovered.

Cogeneration idea was met firstly in Europe and the USA around 1890. Industrial systems had began to use their own power production units with a steam furnace-turbine, operating on coal in the first decades of the 20th century. Many of those units were cogeneration units. Ministers from all twenty three member states in the International Energy Committee of the Organization for Economic Cooperation and Development (OECD) got together in Paris in 1993. Their aim was to make the conditions in which the energy sectors would be able to subscribe as much as possible to a financial development and comfort of the nations, to protect the environment at the same time, thus the following common objectives were put;

- In the energy sector the importance of diversity, efficiency and flexibility were emphasized so basic conditions were provided for a long term energy safety,

- Emergency energy needs were evaluated in the case of capability for a timely and flexible response,

- Usage of energy and environmentally accepted disposal were discussed,

- More environmentally acceptable energy sources encouragement and development were subjected,

- Energy efficiency improvement was discussed for contributing to environmental protection and energy safety in a more efficient manner,

- Marketing of new and improved energy technologies was researched,

- Energy prices were detected to enable market functions in a more efficient manner,
- Free and open commerce and investment safe framework were contributed to the energy efficiency and safety,

- Improving communication and understanding on cooperation of all members of the energy market were aimed.

It is necessary to express the importance of the spread of cogenerations in the countries of organization for economic cooperation and improvement is not only compatible but also contributes to the achievement of all the above objectives. Consequently, the majority of the countries have struggled to promote cogeneration, even if efforts differ from one country to another regarding the efficiency.

Nowadays, cogeneration is regarded as one of the most important techniques to succeed a more efficient utilization of fuels, natural and financial resources savings and environmental protection. The goal of many countries is to overcome obstacles and make it difficult to spread. The relatively high cost of purchase of surplus power from the power corporations as well as the subsidy of investments are implemented by the motivations. Also communication, energy recording and analyses, research and development support are included.

Cogeneration distribution mainly requests good technical support by collaborating groups for regular maintenance operations and repairs of emergency unit break-downs in the commercial building sector, where there is no permanently employed technical personel. This problem seems to be successfully dealt with nearly all countries through the world.

In this chapter, we present the detailed description of Gaski Biogas Engine Powered Cogeneration plant including main and spare parts of this actual cogeneration plant equipments: biogas engine, turbocharger, heat exchangers with different goals within the system, process flows of fuel, water, lubrication oil, and exhaust gas.

3.2 Biogas Engine Powered Cogeneration System

GASKI Biogas Engine Powered Cogeneration System (BPCS) was installed by Gaziantep Municipality Water and Wastewater Works and ILTEKNO Inc. joint venture, and started to generate electricity in 2006. The total installed electricity generation and hot water capacities of the plant is 1.8 MW and 135.11 tons/hr, respectively [59]. The electricity is generated by two biogas engine generator sets, see Figure 3.1. Each engine is four stroke spark ignition engine in a V configuration, one with 12 cylinders and the other with 16 cylinders. Biogas produced from anaerobic digestion of sludge in GASKI WWTP is used as fuel for engines. The engine generator sets were imported from DEUTZ AG Engine Company which is one of the well known largest international company at its sector. Currently, only one engine with 12 cylinders is running in the cogeneration plant and named as TCG2020 12V. The permissible annual electricity production of plant is 14.4 GWh and the annual biogas consumption is nearly 6681.6 tons at designed operating conditions. Plant operation life is determined as twenty five years. The total capital investment of plant was about 1.24 million US dollars.

Figure 3.1 Biogas Engine Powered Cogeneration Sytem

Installed systems in cogeneration plant are; engine generator sets, turbocharger systems, lubrication oil system, compressed air system, cooling system, PLC monitoring control system. The compressed air, as starter, is used to start engine to run. Since engine is turbocharged, there is an intercooler system to cool the charged air before it is sent into the engine cylinders. For engine cooling, an air-water radiator system is chosen. The coolant liquid is water and cycled in a closed loop.

3.3 BPCS Components

3.3.1 Desulphurization ($DeSO_x$) Unit

Biogas produced from anaerobic sludge digestion process is first transferred to $DeSO_x$ unit, Figure 3.2a, to lower the sulphur content to the acceptable legal values. For desulphurization process, iron fillings, Figure 3.2b are used.

Figure 3.2a DeSO$_x$ Unit

Figure 3.2b Iron Fillings

3.3.2 Air-Fuel Mixing Tank

Biogas after desulphurization process is blended with the necessary air in the air-fuel mixing tank, see Figure 3.3, which is leading to the complete combustion of the fuel.

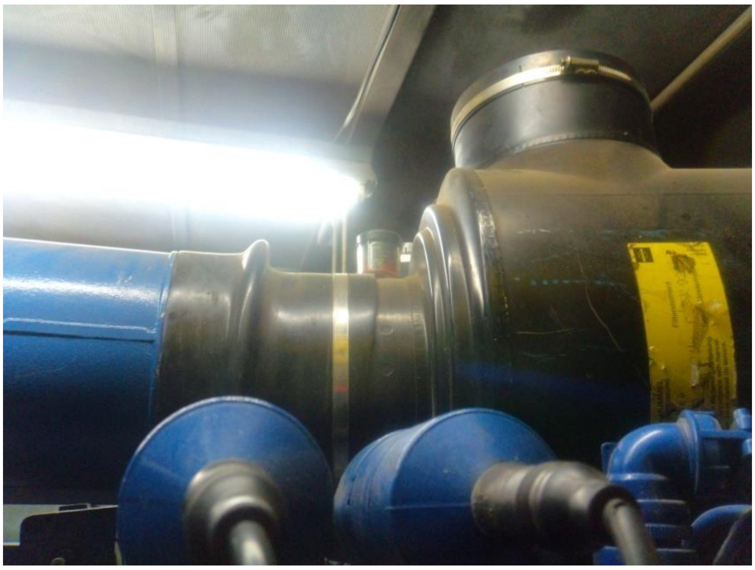


Figure 3.3 Air-Fuel Mixing Tank

3.3.3 Turbocharger

Air- biogas mixture is transferred to the compressor of the turbocharger, Figure 3.4, unit. The compressor of the turbocharger is powered by a turbine which produce its power by using the energy in the exhaust flow of the engine.

Figure 3.4 Turbocharger

When adapting the turbocharger, the combustion attitude of the gas (energy content, combustion speed etc.) must be taken into account. Methane may vary in biogas, this results in changes in combustion behaviour. Biogas composition which is produced in GASKI is given in Table 3.1, At reducing heat value and high inert gas content the combustion speed is decreased which leads to a higher exhaust gas temperature. This causes to a higher charging pressure at the same performance and the compressor of the turbocharger begins pumping.

Table 3.1 The produced biogas composition in GASKI WWTP [77].

Volume	Volumetric values (%)
CH_4	60
CO_2	35
N_2	1.5
H_2	0.3
O_2	0.5
H_2S(2500-3000)	0.25-0.30
LHV (KJ/Kg)	17.892
HHV(KJ/Kg)	21.250

3.3.4 Intercooler

The turbocharger is equipped with an intercooler, to decrease the compressed air-biogas mixture temperature before transmitted to the inlet valve of the engine. In fact, the chemical energy in the gas is transformed into heat energy during combustion. The engine can only partly transform this into mechanical energy. The remaining heat is deployed mainly with the exhaust gas and the coolant. Intercooler is shown at Figure 3.5.

The engine has two circuit cooling systems. The lube oil cooler (lubrication oil heat exchanger), mixture cooler (intercooler), water cooled exhaust pipe and cylinder cooler (exhaust gas heat exchanger) are integrated in the engine cooling circuit. The low temperature intercooler is cooled by a seperate circuit. In this way it is possible to reduce the air-biogas mixture temperature and increase the engine performance. The coolant temperature is controlled and monitored automatically.

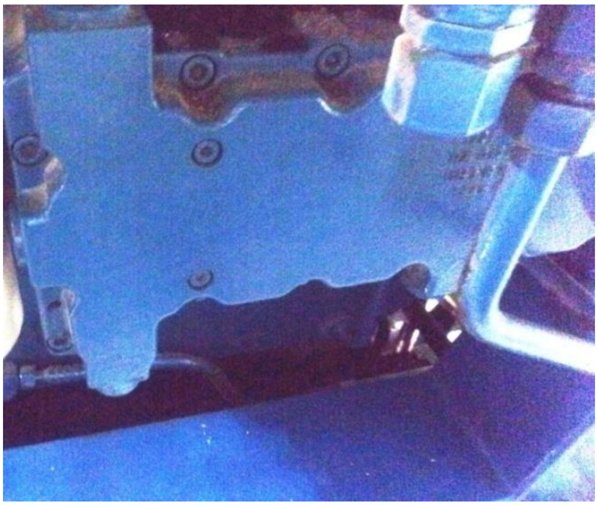


Figure 3.5 Intercooler

3.3.5 Exhaust Gas Heat Exchanger

The exhaust gas from turbine arrives to the exhaust gas heat exchanger (EGHE), a kind of tube heat exchanger as seen in Figure 3.6, for transferring heat to the water which is circulating in the anaerobic digester system of the waste water treatment plant.

3.3.6 Exhaust Filter

The exhaust gas leaving the EGHE is sent to an exhaust filter, Figure 3.7, which is used to capture and reduce CO_2 and CO emissions.

Figure 3.6 Exhaust Gas Heat Exchanger

Figure 3.7 Exhaust Filter

3.3.7 Lubrication Oil Heat Exchanger

The technical advancement of DEUTZ gas engines featuring high efficiencies requires special transcribed lubrication oils with a low ash content. DEUTZ OIL TG-40 LA is recommended for use in DEUTZ gas engines. The lube oil decreases friction of the components which scrub against each other and dissipates heat from the scrubbing positions, the piston head and turbocharger. The lube oil pressure in the engine circuit is adjusted by a lube oil pressure regulating valve. In the cogeneration unit, lubrication oil coming through the engine is cooled in the lubrication oil heat exchanger (LOHE), Figure 3.8.

3.3.8 Other Heat Exchangers

In cogeneration system, there is a typical plate heat exchanger, see Figure 3.9, where the high temperature water flowing through the engine jacket of the gas engine is benefited to heat the water from primary digester units in wastewater treatment plant. Also there is a radiator, see Figure 3.10, which is used to cool the water circulates through intercooler in a cloosed loop.

Figure 3.8 Lubrication Oil Heat Exchanger

Figure 3.9 Plate Type Heat Exchanger

Figure 3.10 Radiator

3.3.9 The Biogas Engine

The engine using biogas as fuel to generate electricity in the cogeneration is DEUTZ TCG 2020 V12; a water cooled four stroke spark ignition, high performance Otto gas engine in a V configuration is shown in Figure 3.11. A special low exhaust emission combustion process has been provided for environmental protection.

Figure 3.11 DEUTZ Biogas Engine set in cogeneration

It was manufactured by DEUTZ AG Company at the factories in Cologne, Germany and imported to Turkey. The engine is turbocharged and compressed air is the starter.

There is an intercooler system for cooling the charged air before it is sent to the engine cylinders. An air-water radiator system, as a heat exchanger, is choosen for engine cooling. The coolant liquid is water and cycled in a closed loop.

3.4 BPCS Process

In the cogeneration process, the biogas is first mixed with air before flowing through the intake valves of the gas engine. When the engine is started, an air-biogas mixture is injected into the compressor of the turbocharger unit. The compressor of the turbocharger is powered by a turbine mounted in the exhaust flow of the engine. The advantage of this is that none of the engine shaft output is used to drive the compressor, and only waste energy in the exhaust is used. The turbocharger is equipped with an intercooler to lower the compressed air-biogas mixture temperature. The exhaust gases leaving the turbine of the turbocharger enter the exhaust gas heat exchanger to transfer heat to the water, which circulates in a closed loop through the primary anaerobic digester unit to supply the necessary heat for the digestion process. The exhaust gas leaving the exhaust gas heat exchanger is sent to an exhaust filter which captures and reduces the CO_2 and CO emissions. The high temperature water flowing through the engine jacket of the gas engine is first used to heat the water from the primary digester units. It then enters the lubrication oil heat exchanger to cool the lubrication oil from the engine. Finally, it returns back to the gas engine after cooling the water by circulating it through an intercooler in a closed loop. Oil is used for lubrication and cooling purposes in the engine components.

3.5 Conclusions

In this chapter, detailed technical information about auxiliary equipments and main flows through the system such as air, fuel oil, lubrication oil, cooling water and exhaust gases of GASKI BPCS facility are presented by using vendor quotations and contractor's guides. Data for the system operation are based on the plant description presented in this chapter.

CHAPTER 4

THERMOECONOMIC COST ACCOUNTING METHODOLOGIES

4.1 Introduction

Engineers have turned to develop new disciplines due to the increasing energy demand of human beings, the concern of exhaustion of natural resources, signs of global warming and waste disposal. Thermoeconomics is one of the most acceptable of these interventions today. It is a kind of natural resource saving science that combines physics and economy by using the second law of thermodynamics.

Power producing plants and chemical plants which formed by a set of subsystems or processes are examples of energy systems. These systems interact with their environment by consuming external sources. These sources are used to obtain products, the ultimate goal of this transaction is to increase economic benefit.

Economic profitability and efficiency with respect to resource consumption determine the production process of a complex energy system. An economic analysis computes the cost of fuel, investment, operation and maintenance for the total plant or even individual components however it can not provide how to distrubute costs among them and its products. On the other hand, thermodynamic analysis computes the efficiency of the individual process of the plant and irreversibilities are located and quantified but it does not have the necessary competence to notice their significance in terms of the overall production process.

Thermoeconomic analysis introduces the application of cost concept to exergy, thus it combines economic and thermodynamic analysis. The exergy of a thermodynamic flow can be described as the minimum amount of work needed for its production, from the reference environment. Since exergy is a thermodynamic function of state and it is formulated by the equivalence between different energy and/or matter flow streams of a plant. A real process is compared with an ideal process by exergetic efficiency. Furthermore irreversibilities in a process are located and quantified by exergy analysis.

Entropy generation, in other meaning irreversibility, is the physical presence that connecting thermodynamics and economics. It presents the destroyed useful energy also true inefficiencies for industrial processes. In an actual plant all common processes are irreversible since exergy is destroyed and consumed, some natural sources are lost forever which resulted in an economic cost. Degree of irreversibility determines the consumption of resources.

Degradation of the exergy is accounted the exergy balance. The input exergy into a process will always be greater than the exergy output;

$$\text{Input Exergy} - \text{Output Exergy} = \text{Irreversibilities} > 0 \tag{4.1}$$

This explanation indicates that irreversibilities occurs during a process. The purpose of this process is detected by the definition of its efficiency. There is an implied classification of the flows crossing the boundary of the system: the flows which are the production objective, the resources required to achieve the production and those that are residual. The second law does not explain this information explicitly however it is the most important conceptual uniting physics with economics. It follows;

$$\text{Resources (F)} - \text{Products (P)} = \text{Residues (R)} + \text{Irreversibilities (I)} > 0 \tag{4.2}$$

Equation (4.2) is extremely important in thermodynamics. On the other hand, efficiency term is defined as;

$$\text{Efficiency} = \text{Product} / \text{Resource} \tag{4.3}$$

It is very old and it measures the quality of a process. If it is desired to produce a specific product, it must be determined in advance because it is external to the system. Once this has been set, the design of the system and its functional structure will be suitable with the aim of using available resources (capital, raw material, man power). Efficiency definitions request a comparison of the product obtained with the resources needed to obtain it. The inverse of efficiency is;

Unit Consumption = Resource / Product (4.4)

Equation (4.4) is the explanation of the unit average cost if resources attribute to the overall plant instead of individual processes. This is the key of thermoeconomics. A concept chain that combines physics and economy can be created as in Figure 4.1.

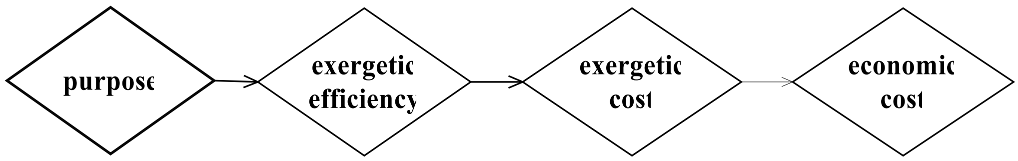


Figure 4.1 Concept chain of thermoeconomics.

Human engineered energy systems are evaluated with efficiency concept. Thermoeconomic analyses investigate this purposive concept. Thus the cost of consumed resources, money and system irreversibilities in terms of the overall production process are identified by thermoeconomic analyses. They are important to emphasize how resources may be used more effectively in order to save them. The economic effect of inefficiencies are impressed by money costs also they are used to improve the cost effectiveness of production processes. The cost of the flow streams and processes in a plant are evaluated to detect the process of cost formation, from the input resources to the final products.

Furthermore thermoeconomics is used for;

- Real cost analyses of plant products based on physical criteria,
- Specific process unit variables optimization for minimizing the final product cost, i.e. global and local optimization,
- To detect the inefficiencies and calculate their economic effects in operating plants, i.e. plant operation thermoeconomic diagnosis,
- To evaluate the various design alternatives or operation decisions and profitability maximization,
- Energy audits.

Thermoeconomic methods are generally classified in two groups, based on cost accounting [43-66], and based on optimization techniques [69-78]. Cost accounting methods are useful to determine the actual cost of products and provide a rational basis for pricing, while optimization methods are applied to find optimum design or operation conditions.

A biogas engine powered cogeneration system was explained in Chapter 3. The temperature, pressure and mass flow rate data, the energy and exergy rates in this system are presented in Table 4.1 that is labeled using the nomenclature shown in Figure 4.2. Four of the thermoeconomic cost accounting methodologies; Exergetic cost theory, modified productive structure analysis, wonergy and specific exergy costing will be applied to the system in this chapter.

4.2 Exergetic Cost Theory (ECT)

This methodology requires the division of the system into units which may be adopted to a component or a set of components. This theory suggests the introduction of a new thermodynamic concept called exergy cost. For a given system whose limits, disaggregation level and production aim of the subsystems have been assigned, the exergy cost of a flow is defined as the amount of exergy needed to produce this flow. A single product and fuel for each component must be defined, and then the necessary calculations have to be performed. Firstly, exergetic costs are determined for each flow and then for each component. After that, cost balance equations for each component and cost allocation equations for external flows into the system are obtained. The solution can be reached when the two following considerations are taken into account: (1) If the fuel definition of a component includes a stream that goes through another component, and is used in it, the unit cost of the stream flowing into and out of the component is the same, and (2) if two or more streams are obtained from a component as the product, the unit cost of those streams are equal. Furthermore the fuel-product definitions are used to improve corresponding matrices. Starting from these matrices, and using the data from the design and operation of the power plant, it is possible to perform a thermoeconomic analysis of the plant.

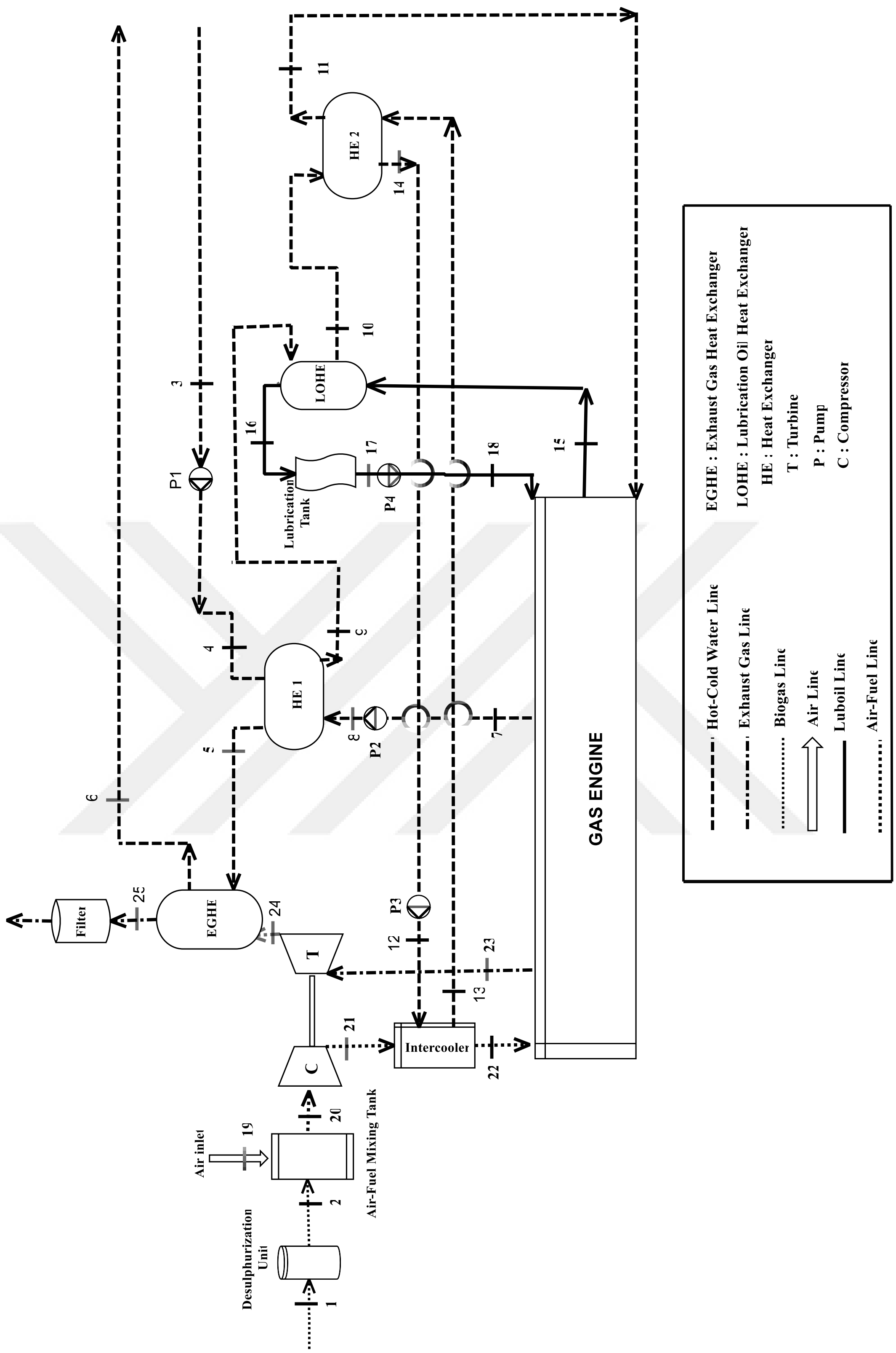


Figure 4.2 Flow schematic of the biogas engine powered cogeneration system.

Table 4.1 Biogas engine powered cogeneration system data, thermodynamic properties, energy and exergy rates in the plant with respect to the state points in Figure 4.2.

State No	Fluid	Pressure P (bar)	Temp. T (°C)	Mass flowrate ṁ (kg/sn)	Enthalpy h (kJ/kg)	Entropy s (kJ/kgK)	Specific energy e (kJ/kg)	Energy rate Ė (kW)	Total exergy rate Ėx (kW)
	Air	1.00	25.00	---	298.60	5.6990	0.000	0.00000	0.00000
0’	Water	1.00	25.00	---	104.80	0.3640	0.000	0.00000	0.00000
0’’	Biogas	1.00	25.00	---	-4650.0	11.620	---	---	---
0’’’	Lub oil	1.00	25.00	---	46.660	0.1620	-	-	0.00000
2	Biogas	1.02	30.10	0.129	-46380	11.640	12.000	1.548000	4046.40
3	Water	5.25	75.80	20.88	317.70	1.0250	212.90	4457.800	350.900
4	Water	6.20	75.80	20.88	317.80	1.0250	213.00	4447.440	352.800
5	Water	6.10	82.80	20.88	347.10	1.1080	242.30	5059.220	447.300
6	Water	3.40	88.00	20.88	368.70	1.1690	263.90	5510.230	518.700
7	Water	2.80	88.40	15.61	370.40	1.1740	265.60	4146.010	391.400
8	Water	7.60	88.50	15.61	371.20	1.1740	266.40	4158.500	400.000
9	Water	7.50	72.40	15.61	303.60	0.9830	198.80	3103.268	234.300
10	Water	7.30	77.90	15.61	326.70	1.0500	221.90	3463.859	285.900
11	Water	7.20	78.50	15.61	329.20	1.0570	224.40	3502.884	291.700
12	Water	4.55	50.00	11.28	209.70	0.7035	104.90	1183.270	49.8300
13	Water	4.50	52.10	11.28	218.50	0.7306	113.70	1282.530	58.3700
14	Water	1.10	50.00	11.28	209.40	0.7037	104.60	1179.800	47.5300
15	Lub oil	4.69	100.6	20.00	202.90	0.6270	156.24	3124.800	357.700
16	Lub oil	4.50	89.00	20.00	177.30	0.5570	130.70	2612.800	259.400
17	Lub oil	1.00	85.00	20.00	168.30	0.5330	121.60	2432.800	220.900
18	Lub oil	6.90	87.00	20.00	173.20	0.5450	126.60	2530.800	248.700
19	Air	1.00	25.00	1.387	298.60	5.6990	0.0000	0.000000	0.00000
20	Air-fuel	1.00	25.00	1.500	298.60*	5.6990*	0.0000	0.000000	4046.40
21	Air-fuel	1.90	116.9	1.500	391.20*	5.7860*	92.600*	126.9500*	4154.13
22	Air-fuel	1.90	51.00	1.500	324.70*	5.5990*	26.140*	35.83000*	4136.23
23	Exhaust gas	2.40	460.0	1.500	749.40	6.3750	450.80	676.2000	374.300
24	Exhaust gas	1.17	360.6	1.500	642.90	6.4250	344.40	516.5000	192.250
25	Exhaust gas	1.00	65.00	1.500	338.80	5.8260	55.340	60.34000	3.69200

*These values correspond to air not the air-fuel mixture; during analysis, air state properties and biogas state properties are calculated separately and their summations are used.

4.2.1 Exergetic Cost Definitions

Some explanations are necessary that should be emphasized before implementing the analysis.

The incidence matrix; A (i × ь), is the representation of the connection between i subsystems with ь flows through the system. It helps to find the destroyed exergy. For a given state, the exergy of a flow, $\dot{E}x$, and destroyed exergy, $\dot{E}x_{dest}$, corresponding to each subsystem can be shown as,

$$A \times \dot{E}x = \dot{E}x_{dest} \tag{4.5}$$

where $\dot{E}x$ is the exergy vector and $\dot{E}x_{dest}$ is the destroyed exergy vector.

The aggregation level, is the combination of subsytems which make up the whole system. It varies according to the limitation of the system and each aggregation level has its incidence matrix. Any system with a defined aggreation level is specified by an incidence matrix.

The fuel-product, for any component or system -both fuel and product- is expressed in terms of exergy as $\dot{E}x_F$ or $\dot{E}x_P$. There can be a single exergy or the difference or sum of two or more exergetic flows. Table 4.2 shows the fuel-product definitions for our system. For example, consider the heat exchanger 1 (HE1) in Figure 4.1 where the fuel and product is defined as the corresponding exergy differences ($\dot{E}x_8$- $\dot{E}x_9$) and ($\dot{E}x_5$- $\dot{E}x_4$).

Residue, Some flows are stated as completely or partially useless within the systems. For example, in coal fired power plants ash from the boiler is the residue. In our system, stream 25 is considered to be a residue.

The efficiency and unit consumption of a system, Exergetic efficiency for any power plant is defined as $\varepsilon \equiv \dot{E}x_P / \dot{E}x_F$, and unit exergetic consumption is $\kappa \equiv 1/\varepsilon = \dot{E}x_F / \dot{E}x_P$. It is obvious that κ is greater than 1 given the implications of the second law of thermodynamics.

The exergetic cost, is specified as, $\dot{E}x^*$, or the amount of exergy per unit time required to produce a flow. $\dot{E}x^*$, like $\dot{E}x$, is a thermodynamic function [38].

The costs of exergetic flows are determined according to the limits of the system; hence it is not possible to define an absolute exergetic cost for a flow. Where a flow exceeds the limits of a system, its exergetic cost is equal to its exergy, since no exergy has so far been consumed to obtain it. For a defined subsystem, the exergetic cost of the fuel is equal to the exergetic cost of the product; $\dot{E}x^*_{F,i} = \dot{E}x^*_{P,i}$.

The exergetic cost balance equation for a system is formed with the help of its incidence matrix, *A*, as follows

$$A \times \dot{E}x^* = 0 \tag{4.6}$$

where $\dot{E}x^*$ is the exergetic cost vector for dimension m, which is the number of flows through the system.

Unit exergetic cost, κ^*, is a flow's unit exergetic cost and it is defined by $\kappa^* = \dot{E}x^* / \dot{E}x$. A flow is characterized by its unit exergetic cost; hence, it is a property like exergy and temperature. Its value demonstrates the inefficiency of the production process, therefore greater unit exergetic cost emphasizes the more exergy destroyed to produce a flow. All the flows in the system have two unit exergetic costs, one is for fuel $\kappa^*_F = \dot{E}x^*_F / \dot{E}x_F$, the other is for product $\kappa^*_P = \dot{E}x^*_P / \dot{E}x_P$.

Table 4.2 Fuel-product definition of the biogas engine powered cogeneration system.

i	Component	Fuel	Product
1	Compressor	$\dot{W}_T$	$\dot{E}x_{21} - \dot{E}x_{20}$
2	Turbine	$\dot{E}x_{23} - \dot{E}x_{24}$	$\dot{W}_T$
3	Intercooler	$\dot{E}x_{13} - \dot{E}x_{12}$	$\dot{E}x_{21} - \dot{E}x_{22}$
4	EGHE	$\dot{E}x_{24} - \dot{E}x_{25}$	$\dot{E}x_6 - \dot{E}x_5$
5	HE1	$\dot{E}x_8 - \dot{E}x_9$	$\dot{E}x_5 - \dot{E}x_4$
6	HE2	$\dot{E}x_{13} - \dot{E}x_{14}$	$\dot{E}x_{11} - \dot{E}x_{10}$
7	LOHE	$\dot{E}x_{15} - \dot{E}x_{16}$	$\dot{E}x_{10} - \dot{E}x_9$
8	P1	$\dot{W}_{P1}$	$\dot{E}x_4 - \dot{E}x_3$
9	P2	$\dot{W}_{P2}$	$\dot{E}x_8 - \dot{E}x_7$
10	P3	$\dot{W}_{P3}$	$\dot{E}x_{12} - \dot{E}x_{14}$
11	P4	$\dot{W}_{P4}$	$\dot{E}x_{18} - \dot{E}x_{17}$
12	Gas Engine	$\dot{E}x_{22}$	$\dot{W}_{GE}$
	The System	$\dot{E}x_{22}$	$\dot{W}_{GE} + \dot{E}x_6 - \dot{E}x_3$

4.2.2 Exergetic Cost Determinations

Basic information is given in the definition of exergetic cost. This information is used to form the rules formulated by Valero [40];

<u>Rule 1</u> The fuel or product exergy of a component should be positive, $\dot{E}x_F$, $\dot{E}x_P > 0$.
e.g. for component 7, LOHE.

$$\dot{E}x_{F,7} = \dot{E}x_{15} - \dot{E}x_{16} \tag{4.7}$$

$$\dot{E}x_{15} > \dot{E}x_{16} \tag{4.8}$$

$$\dot{E}x_{P,7} = \dot{E}x_{10} - \dot{E}x_9 \tag{4.9}$$

$$\dot{E}x_{10} > \dot{E}x_9 \tag{4.10}$$

<u>Rule 2</u> In a component, the unit exergetic cost of each fuel is greater than or equal to one, $\kappa_F^* \geq \dot{E}x_F^* / \dot{E}x_F \geq 1$, also the streams that make up the fuel have the same unit exergetic cost.
e.g. for component 5, HE.

$$\dot{E}x_{F,5} = \dot{E}x_8 - \dot{E}x_9 \tag{4.11}$$

$$\kappa_8^* = \kappa_9^* \tag{4.12}$$

$$\dot{E}x_8^* / \dot{E}x_8 = \dot{E}x_9^* / \dot{E}x_9 \tag{4.13}$$

$$(1)\dot{E}x_8^* + (-x_5)\dot{E}x_9^* = 0 \tag{4.14}$$

$$x_5 = \dot{E}x_8 / \dot{E}x_9 \tag{4.15}$$

<u>Rule 3</u> If a component has more than one product, all the products have the same unit exergetic cost in the absence of any external exergetic application. Furthermore, the unit exergetic cost of the product is always greater than the unit exergetic cost of the fuel for a generic component, $\kappa_P^* > \kappa_F^*$. In our system all components have a single product.

<u>Rule 4</u> Residue or loss must appear explicitly as products in a subsystem however, the exergetic cost of any loss or residue is equal to zero, $\dot{E}x_L^* = 0$, this situation results in exergetic cost equality for fuel and product, which is valid for any component, $\dot{E}x_F^* = \dot{E}x_P^*$.

These rules will help to determine unit exergetic costs which are directly interconnected with exergetic costs. Thus, after obtaining the unit exergetic costs of flows, the next step is to calculate the exergetic costs of components. The incidence matrix, A, which explicitly shows the inputs and outputs of the cogeneration system is not enough on its own. Therefore, the fuel and product matrices, A_F, and, A_P as seen in Table 4.2, are used to determine the exergetic cost for each component.

$$A = A_F - A_P \tag{4.16}$$

$$\dot{E}x_F = A_F \times \dot{E}x \tag{4.17}$$

$$\dot{E}x_F^* = A_F \times \dot{E}x^* \tag{4.18}$$

$$\dot{E}x_P = A_P \times \dot{E}x \tag{4.19}$$

$$\dot{E}x_P^* = A_P \times \dot{E}x^* \tag{4.20}$$

The relationship between the thermodynamics and economics to reach the thermoeconomic costs is given in the next section.

4.2.3 Thermoeconomic Cost Definitions

To calculate the price of fuels crossing the system, and the amortization, maintenance and overhead costs of the subsystems contained in a bounded system with a prescribed aggregation level, some necessary definitions [40] are given below.

The thermoeconomic cost, $\dot{C}$, of a flow is the amount of monetary units per hour required to obtain this flow.

The unit thermoeconomic cost, c^*, of a flow is the cost of each unit of exergy consumed in producing this flow. Thermoeconomic cost is related with the unit thermoeconomic cost in Equation (4.21).

$$\dot{C} = c^* . \dot{E}x^* \tag{4.21}$$

The unit exergoeconomic cost, c, of a flow is the cost of each unit of exergy concerned with this flow. Equation (4.22) is the relation of thermoeconomic cost with the unit exergoeconomic cost.

$$\dot{C} = c . \dot{E}x \tag{4.22}$$

The unit exergetic cost, κ*, gives a relationship between the unit exergoeconomic cost and the unit thermoeconomic cost. It is denoted as,

$$c = c^{*} . \kappa^{*} \quad (4.23)$$

Having defined these sets of costs, it is not difficult to form the thermoeconomic cost balance equations.

4.2.4 Thermoeconomic Cost Balance

The thermoeconomic cost balance is achieved by the addition of economics to exergy. The incidence matrix, and the cost of maintenance and operation of the production system, $\dot{Z}$, give indications about the thermoeconomic cost.

$$A \times \dot{C} + \dot{Z} = 0 \quad (4.24)$$

$\dot{Z}$, monetary units per hour, can be computed by applying the usual procedures for evaluating equipment costs [106,107]. The thermoeconomic costs of the flows through the system are determined by the application of Equation (4.24). In the case of the components, if product and fuel are defined for the specified unit, it can be determined that the thermoeconomic cost of the product is equal to the thermoeconomic cost of the fuel used to generate it, plus the cost of maintenance and operation of the production system.

$$\dot{C}_P = \dot{C}_F + \dot{Z} \quad (4.25)$$

The thermoeconomic costs for fuel and product are related by unit thermoeconomic and exergetic costs as given in Equation (4.26) and (4.27).

$$\dot{C}_F = c_F^{*} . \dot{E}x_F^{*} = (c_F^{*} . \kappa_F^{*}). \dot{E}x_F = c_F . \dot{E}x_F \quad (4.26)$$

$$\dot{C}_P = c_P^{*} . \dot{E}x_P^{*} = (c_P^{*} . \kappa_P^{*}). \dot{E}x_P = c_P . \dot{E}x_P \quad (4.27)$$

The steps to calculate thermoeconomic costs from the beginning are as follows;

i. Specify the incidence matrix, *A*, for the system and the exergetic values, $\dot{E}x$, of all the flows.

ii. Define the fuel and product for all subsytems and form the corresponding matrices, A_F , and A_P.

iii. Calculate the exergetic costs, $\dot{E}x^*$, of the flows by solving Equation (4.6) then calculate the other exergetic costs, and $\dot{E}x_F^*$, $\dot{E}x_P^*$, for components and the unit exergetic costs, κ^*, κ_F^* , κ_P^*.

iv. Find the amortization vector, $\dot{Z}$.

v. Obtain the unit economic costs, $c^*$and c , and also the thermoeconomic cost $\dot{C}$.

vi. Compute the thermoeconomic costs of fuel $\dot{C}_F$ and product $\dot{C}_P$ for each omponent.

4.3 Modified Productive Structure Analysis (MOPSA)

In this method, an exergy costing system without flow cost calculations was proposed by Kwak et al. [49]. Cost balance equations, which are valid for any component of the cogeneration system, are obtained by assigning a unit exergy cost to each disaggregated exergy in the stream at any state. Subsequently, a set of equations for the unit exergy costs is formed for the system. The interactions between components in the costing process are naturally enclosed in the set of equations, i.e., a particular exergy cost in one component contributes to the evaluation of the exergy cost in another component. The monetary evaluations of various exergy costs, as well as the production cost of the electricity, are acquired by solving the set of equations for the unit exergoeconomic costs. In addition, the lost cost for each component of the system, which is connected to entropy generation processes, can be obtained by solving the cost balance equations.

4.3.1 Thermoeconomic Cost Balance for MOPSA

A general exergy balance equation, applicable to any unit of a cogeneration system can be formulated by utilizing the first and second law of thermodynamics. To emphasize the exergy losses due to heat transfer, the exergy balance equation for the nonadiabatic components is modified. The general exergy balance equation for this theory can be written as follows,

$$\dot{E}x^{CHE} + \left(\sum_{inlet} \dot{E}x_j^T - \sum_{outlet} \dot{E}x_j^T \right) + \left(\sum_{inlet} \dot{E}x_j^M - \sum_{outlet} \dot{E}x_j^M \right)$$

$$+ T_0 \left(\sum_{inlet} \dot{S}_j - \sum_{outlet} \dot{S}_j + \dot{Q}_{CV} / T_0 \right) = \dot{W} \qquad (4.28)$$

The term $\dot{E}x^{CHE}$ in Equation (4.28) denotes the rate of chemical exergy flow of fuel in the plant, and the term $\dot{Q}_{CV}$ shows the heat transfer interaction between a component and the environment. Specifying a unit exergy cost for every decomposed exergy stream, the cost balance equation corresponding to the exergy balance equation given in Equation (4.29) is shown below,

$$Ex^{CHE} c_0 + \left(\sum_{inlet} \dot{E}x_j^T - \sum_{outlet} \dot{E}x_j^T \right) c_T + \left(\sum_{inlet} \dot{E}x_j^M - \sum_{outlet} \dot{E}x_j^M \right) c_M$$

$$+ \left(\sum_{inlet} \dot{E}x_j^M - \sum_{outlet} \dot{E}x_j^M \right) d_M + \left(\sum_{inlet} \dot{E}x_j^T - \sum_{outlet} \dot{E}x_j^T \right) d_T$$

$$+ T_0 \left(\sum_{inlet} \dot{S}_j - \sum_{outlet} \dot{S}_j + \dot{Q}_{CV} / T_0 \right) c_S + \dot{Z} = \dot{W} c_W \qquad (4.29)$$

The unit exergoeconomic costs according to thermal and mechanical exergies,c_T, c_M are for gas streams and d_T, d_M are for the water and lubrication oil streams. The term $\dot{Z}$ comprises all the financial charges associated with owning and operating the plant components as mentioned in the exergetic cost theory. In this method the total exergy is divided into thermal and mechanical parts. Equations (4.28) and (4.29) are the two main equations used in MOPSA analysis and Equation (4.29) yields the productive structure of the system.

4.3.2 Cost Balance Equations of MOPSA

The general cost balance equation is given in Equation (4.29) for MOPSA. Then for each component in our cogeneration system, shown in Figure 4.2, cost balance equations can be derived. When the cost balance equation is used for a component, a new unit cost must be attributed to the component's principal product [50], whose unit cost is expressed in bold. After the unit cost is assigned to the main product of the components, the cost balance equations for the system are formulated.

4.4 Wonergy Method

This methodology was introduced by Kim [53] for the fields of cost allocation, cost optimization and cost analysis. In this method various energies combining enthalpy and exergy are integrated in “Wonergy”, a fusion of worth and energy. Wonergy is defined as an energy that can equally evaluate the worth of each product.

The first law of thermodynamics emphasizes the energy balance equation for the i-th component and overall system as follows,

$$\dot{W}_i + \dot{E}_{Q,i} = \dot{E}_{F,i} - \dot{E}_{P,i} - \dot{E}_{L,i} \tag{4.30}$$

$$\dot{W} + \dot{E}_Q = \dot{E}_F^{CHE} - \dot{E}_L \tag{4.31}$$

where $\dot{W}$ and $\dot{E}_Q$ are the quantity of total work and heat, which are the desirable final products of a cogeneration system, $\dot{E}_{F,i}$ is the fuel inlet, $\dot{E}_{P,i}$ is the product output and $\dot{E}_{L,i}$ is the heat lost into the environment. The exergy balance equation for the i-th component and overall system is written as follows,

$$\dot{W}_i + \dot{E}x_{Q,i} = \dot{E}x_{F,i} - \dot{E}x_{P,i} - \dot{E}x_{L,i} \tag{4.32}$$

$$\dot{W} + \dot{E}x_Q = \dot{E}x_F^{CHE} - \dot{E}x_L \tag{4.33}$$

where $\dot{E}x_Q$ is the quantity of hot water exergy. The tabulated values of these energy and exergy equations will be given results and discussion section.

The energy balance equations agree with the exergy balance equations. Therefore, combining energy and exergy in Wonergy, and then modifying the symbols of $\dot{E}$ and $\dot{E}x$ with $\dot{K}$, the Wonergy balance equation can be written as follows,

$$\dot{W}_i + \dot{K}_{Q,i} = \dot{K}_{F,i} + \dot{K}_{P,i} - \dot{K}_{L,i} \tag{4.34}$$

$$\dot{W} + \dot{K}_Q = \dot{K}_F - \dot{K}_L \tag{4.35}$$

The cost balance equation requires that the sum of the output costs must be equal to the sum of the input costs for the whole system,

$$c_w \dot{W} + c_Q . \dot{E}_Q = \dot{C}_0 + \dot{C}_{CO_2} + \dot{Z}_{ID} + \sum \dot{Z} \quad (4.36)$$

where c_w and c_Q are the unit exergoeconomic cost of work and heat produced by the system, $\dot{C}_{CO_2}$ is the environmental pollution cost flow, such as carbon emission, $\dot{Z}_{ID}$ is the sum of the indirect cost flow passing from the outside to the system, and $\dot{Z}$ is the capital investment. The small environmental pollution cost flow for our system is neglected, and there is no indirect cost flow passing from the outside to the system so, $\dot{C}_{CO_2}$ and values $\dot{Z}_{ID}$ are equal to zero.

The Wonergy method divides the system into three components: the common components [₵] associated with work and heat production, the work-only components [W] associated with work production, and the heat-only components [Q] associated with heat production. It is obvious from the Wonergy equations that the summation of $\dot{K}_{F,i}$ and $\dot{K}_{P,i}$ for all components is exactly zero, as expressed in Equation (4.38). Thus, multiplying ($\dot{K}_{₵} + \dot{K}_W + \dot{K}_Q = \sum K_{F,i} + K_{P,i}$) by the wonergetic unit cost c_K, and adding the term to Equation (4.36), that the wonergetic cost balance equation can be formed,

$$c_w . \dot{W} + c_Q . \dot{E}_Q = \dot{C}_0 + \dot{Z}_W + \dot{Z}_Q + c_K \ (\dot{K}_{₵} + \dot{K}_W + \dot{K}_Q) \quad (4.37)$$

This method asserts that the input cost flow in the common components is fairly distributed to work and heat by Wonergy, the input cost flow in the work-only components is entirely distributed for producing work, and the input cost flow in the heat-only components is completely distributed for producing heat. According to this idea, Equation (4.36) for all components is split up into Equation (4.38) for [₵] components, Equation (4.39) for [W] components and Equation (4.40) for [Q] components.

$$\dot{K}_{₵} + \dot{K}_W + \dot{K}_Q = 0 \quad (4.38)$$

$$0 = \dot{C}_0 + c_K . \dot{K}_{₵} \quad (4.39)$$

$$c_w . \dot{W} = \dot{Z}_W + c_K . \dot{K}_W \quad (4.40)$$

$$c_Q . \ \dot{E}_Q = \dot{Z}_Q + c_K . \dot{K}_Q \quad (4.41)$$

where each value of $\dot{K}_W$ and $\dot{K}_Q$ is positive and $\dot{K}_{₵}$ is negative. The signs for these values can be checked from the values of $\dot{E}_F$, $\dot{E}_P$, $\dot{E}x_F$, $\dot{E}x_P$ and from Tables (6.14) and (6.15). If these equations are rearranged, the exergoeconomic cost of work, c_w, the exergoeconomic cost of heat, c_Q, the work cost flow rate, $\dot{C}_W$, and the heat cost flow rate, $\dot{C}_Q$, can be determined as follows,

$$c_w = ƙ_W \cdot \frac{\dot{C}_0}{ƙ_W.\dot{W} + ƙ_Q.\,\dot{E}_Q} + \frac{\dot{Z}_W}{\dot{W}} \tag{4.42}$$

$$\dot{C}_W = c_w.\,\dot{W} = \dot{K}_W \cdot \frac{\dot{C}_0}{\dot{K}_W + \dot{K}_Q} + \dot{Z}_W \tag{4.43}$$

$$c_Q = ƙ_Q \cdot \frac{\dot{C}_0}{ƙ_W.\dot{W} + ƙ_Q.\,\dot{E}_Q} + \frac{\dot{Z}_Q}{\dot{E}_Q} \tag{4.44}$$

$$\dot{C}_Q = c_Q.\,\dot{E}_Q = \dot{K}_Q \cdot \frac{\dot{C}_0}{\dot{K}_W + \dot{K}_Q} + \dot{Z}_Q \tag{4.45}$$

where $ƙ_W = \dot{K}_W / \dot{W}$ and $ƙ_Q = \dot{K}_Q / \dot{E}_Q$. $\dot{K}$ is the Wonergy input and ƙ is the Wonergy input ratio. Equations (4.42) to (4.45) help solve the cost problem for the system.

4.5 Specific Exergy Costing Method (SPECO)

Specific exergy costing is a systematic and general methodology to calculate efficiencies and costs in thermal systems [55] such as cogeneration. This method models the fuel and product definitions as the exergy additions to, and removal from, a component. The cost rates are obtained by using basic principles of business administration. The specific exergy costing method includes three steps. The first step is the identification of energy and exergy flows through the system components. The calculated energy and exergy for each state of the flows are given in Table 4.1. The second is an explanation of the fuel and product rule, the main principle of SPECO, to determine the exergoeconomic cost of the flows. Finally, the exergetic cost balance and auxiliary equations for the subsystems are derived.

4.5.1 Fuel and Product Rule

The fuel rule is related to the removal of exergy from a flow through a component. The definition of fuel should include the difference between the inlet and outlet flow. It indicates that the total cost regarding the removal of exergy is the same as the cost at which the extracted exergy is provided to the same flow in the next component.

The product rule is concerned with the supply of exergy flow through the component. It states that each exergy unit is provided to any flow corresponding to products with the same exergoeconomic cost. This cost can be obtained using the cost balance or other equations formed by applying the fuel rule. Figure 4.3 is a schematic of a component in any system to explain fuel, product and auxiliary costing equations.

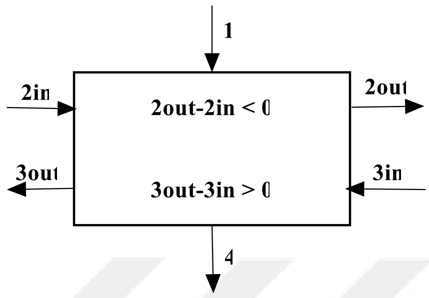


Figure 4.3 Inlet and outlet exergetic streams for a component in any system.

All flows represented in Figure 4.3 are exergy streams. The exit stream of the second flow is smaller than its inlet stream, so the fuel (F) rule introduces Equations (4.46) and (4.47).

$$c_{2in} = c_{2out} \tag{4.46}$$

$$c_4 = \frac{\dot{C}_{3out} - \dot{C}_{3in}}{\dot{E}x_{3out} - \dot{E}x_{3in}} \tag{4.47}$$

The requirements of the fuel (F) and product (P) rule are defined, then the cost balance equations are formed in the next section.

4.5.2 Cost Balance Equations for SPECO

According to the inlet and outlet flows, which carry fuel exergy into a component or product exergy from it, the cost balance equations are written as follows,

$$\dot{C}_F = c_F . \dot{E}x_F \tag{4.48}$$

$$\dot{C}_P = c_P . \dot{E}x_P \tag{4.49}$$

$$\dot{C}_W = c_W . \dot{W} \tag{4.50}$$

$$\dot{C}_Q = c_Q . \dot{Q} \tag{4.51}$$

Here c_F , c_P , c_W, c_Q define exergoeconomic costs per unit of exergy for fuel (inlet), product (outlet), work and heat flows, and $\dot{C}_F$, $\dot{C}_P$, $\dot{C}_W$, $\dot{C}_Q$ are thermoeconomic costs related to the corresponding exergy streams. Generally, SPECO defines the cost balance equation for the i-th subsystem [22],

$$c_{F,i}\dot{E}x_{F,i} - c_{P,i}\dot{E}x_{P,i} \pm c_{W,i}\dot{E}x_{W,i} \pm c_{Q,i}\dot{E}x_{Q,i} + \dot{Z}_i = 0 \quad (4.52)$$

SPECO cost balance equations for each component in the cogeneration system, shown in Figure 4.1, can be derived from the cost balance equation given in Equation (4.52).

4.6 Conclusions

In this chapter, we provided general principles, terminology, and formulation of thermoeconomic analysis approaches: ECT, MOPSA, Wonergy and SPECO with their all mathematical foundations. The procedure and formulation are applicable to all energy conversion systems including biogas engine powered cogeneration systems. Detailed formulations considering the operation of the entire system and components will be provided in Chapter 6.

CHAPTER 5

THERMOECONOMIC OPTIMIZATION METHODS

5.1 Introduction

Many fields of science and technology; the physical sciences, engineering, economics, try to find the best way to achieve a specified goal. First of all best type of energy system must be determined according to the energy needs, followed by the best system configuration (components and interconnections). Technical characteristics of each component; dimensions, material, capacity, are important. The best flow rates, pressures and temperatures of the various working fluids must be choosen which require the best operating point of the system at each instant of time. If there are many plants are present to operate on a certain region, it must be specified that which plants operate, and at what load under certain conditions. Furthermore, their operation and maintenance should be scheduled in time. In fact optimization is the most valid answer to these types of necessities which use a systematic procedure.

A workable system, a system that performs the assigned task within the imposed constraints, is aimed in a conventional design procedure. However, there will be more than one workable design maybe any number of better designs that the conventional procedure may not state. Optimization reveals the best (under certain criteria and constraints) design and the best operational point of the system automatically, with no need for the designer to study and evaluate one by one the multitude of possible variations.

Optimization increases the quality and capacity of the plants while reducing costs in order to be competitive. It also fulfills ever increasing specification as well as considering reliability and safety, observes strict pollution regulations, and saves energy and material resources. Saving time and increasing the designers creativity are the other advantages of optimization.

5.2 Optimization Levels of Energy Systems

Requirements of energy systems direct the optimization process at three levels,

Synthesis optimization, components appear in a system and their interconnections are denoted by the term synthesis. The flow diagram of the system can be drawn after the synthesis of a system has been successfully composed.

Design optimization, The word design implies the technical characteristics of the components and the properties of the substances entering and exiting each component at the nominal load of the system. The nominal load identifies the design point of the system. Design may include synthesis however in order to express the various levels of optimization and there is no any better term, the word design is used with the particular meaning given here.

Operation optimization, For a given system (i.e. one in which the synthesis and design are known) under specified conditions, the optimal operating point is identified by the operating properties of components and substances in the system (speed of revolution, power output, mass flow rates, pressures, temperatures, composition of fluids, etc.). If complete optimization is aimed, each level cannot be considered in complete isolation from the others. Time dependent optimization needs one more dimension, which causes to increase the complexity of the problem.

5.3 Formulation of The Optimization Problem

The general optimization problem consists of a determination of the extremum (minimum or maximum) of an objective function under certain constraints [73]. It is mathematically represented as,

minimize $f(x)$ (5.1)

with respect to $x = (x_1, x_2, \ldots, x_n)$ (5.2)

subject to the constraints $h_j(x) = 0 \quad j = 1, 2, \ldots, m$ (5.3)

$$g_k(x) \geq 0 \qquad k = 1, 2, \ldots, J \tag{5.4}$$

where

x, set of all the independent variables,

h_i, equality constraint functions (strong constraints), they help to simulate the system and are derived by an energetic, exergetic and economic, analysis,

g_k, inequality constraint functions (weak constraints), which determine the design and operation limits, state regulations, safety requirements,

Independent variables are arranged into three sets,

$$x \equiv (v, w, z) \tag{5.5}$$

where

v, shows the set of independent variables for operation optimization (load factors of components, mass flow rates, pressures and temperatures of streams, etc.),

w, stresses the set of independent variables for design optimization (nominal capacities of components, mass flow rates, pressures and temperatures of streams, etc.),

z, indicates the set of independent variables for synthesis optimization; for each component there is only one variable of this type, indicating whether the component exists in the optimal configuration or not; it may be a binary (0 or 1), an integer, or a continuous variable such as the rated power of a component, with a zero value.

Then, Equation (5.1) is rewritten,

$$\text{minimize } f(v,w,z) \tag{5.6}$$

$$\text{with respect to } (v, w, z) \tag{5.7}$$

For a given synthesis of the system, i.e. for given z, the problem evaluated as design and operation optimization,

$$\text{minimize } f_{design}(v,w) \tag{5.8}$$

Furthermore, if the system is completely specified (both z and w are given), then an operation optimization problem is formulated,

$$\text{minimize } f_{optimization}\ (v) \tag{5.9}$$

Maximization is stated by Equation (5.1),

$$\min f(\mathbf{x}) = \max \{- f(\mathbf{x})\} \tag{5.10}$$

5.4 Objective Functions

Which criterion will be optimized is very important and the answer depends on the particular application; for example, in an aircraft or space vehicle, minimum weight of the system may be the desicion variable; in an automobile, minimum size of the system can be considered; in a stationary power plant, the minimum life cycle cost of the system may be the desicion variable. Other objective functions for energy systems comprise; maximization of efficiency, minimization of fuel consumption, minimization of exergy destruction, maximization of the net power density, minimization of emitted pollutants, maximization of the internal rate of return, minimization of the payback period, etc. Some of these are interpreted as technical objectives, while the rest are thermoeconomic objectives. As a result, the final design may deviate from the lowest cost, for example by considering environmental, social, aesthetic or other aspects.

5.5 Independent Variables

Each component and the system as a whole is expressed by a set of quantities. Certain of those are fixed by external conditions (e.g., environmental pressure and temperature, fuel price) and are called parameters. The remaining are variables and their value can change during the optimization procedure. Those variables, the values of which do not affected by other variables or parameters, are called independent variables. On the other hand dependent variables can be determined by the solution of the system of equality constraints. The number of dependent variables is equal to the number of equality constraints. Thus, the duty of the optimization procedure is to determine the values of the independent variables x. If the number of equality constraints is higher than the number of all the variables, then the problem is over specified and there is no solution for optimization.

5.6 Equality and Inequality Constraints

Equations (5.3) and (5.4) are expressions which involve design characteristics and operating parameters or variables of the components as well as the system as a whole. On the other hand, inequality constraints are imposed by the safety and operability of the system. The set of equality and inequality constraints is derived by an analysis of the system and help to constitute the mathematical model of the system. Models may initially be developed at the level of each component, which are then integrated to form the model of the whole system.

5.7 Thermoeconomic Optimization Methods

Thermoeconomics explained before is a technique, which combines thermodynamics and economics for the evaluation, improvement and optimization of power producing systems. A proper balance between an appropriate thermodynamic measure and capital expenditure are requested for economic considerations in order to achieve a minimum product cost. By introducing dissipation (exergy destruction) as a unified extensive measure, thermoeconomics evaluates the complex system as made up of a number of dissipative zones, for each of which the relative economic value of dissipation is estimated. A local balance between capital expenditure and dissipation is then made in each zone. Two basic concepts, exergy and the internal economy are introduced. Exergy ensures a common basis for evaluation and comparison of processes, and a consistent way of catching dissipations. On the other hand, a structure of internal unit costs represents a fictitious internal economy which provide convenience to evaluate the overall relative economic values of local dissipations.

The balance between thermodynamic measures and capital expenditures is an economic feature, which applies to the complex plant as a whole and to each of its components individually. This feature allows optimization to decompoze the system physically without violating the mathematical disciplines.

5.8 Thermoeconomic Functional Analysis (TFA)

This method is developed by Frangopoulos [73,74]. The definitions and application prospectus required by the method will be described in the following sections.

5.8.1 Definitions

A power plant is composed of a set of subsystems which are in relation with other. Every system has the principle of giving a useful end like ''product'' in other meaning ''function''. Therefore functional analysis pays attention to describe the functions of the system as a whole or each unit seperately in a formal and documented way. An important point is to recognize a unit from a component. A cooling tower or a cooling water circulating pump are components on their own, on the other hand they are not seperate units when combined with condenser. Because they perform only one function. Requested investigations and existing informations determine the number of units therefore number of units is not unique.

5.8.2 Functional Diagram

Functional analysis requests a functional diagram which establishes the relations of the unit functions. Distributions of unit functions are expressed by arrows from the unit or incoming functions from other units are expressed arrows to the unit. Each unit with its inlet (I), and output (O) is represented as in Figure 5.1.

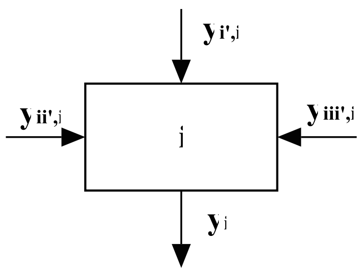


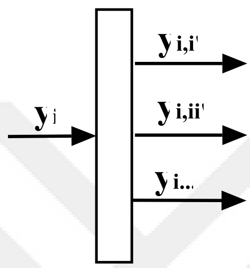
Figure 5.1 I-O of a unit.

i, i th unit of the system (i =1,2,..)

y_i, the product, describing the appropriate function of unit i

$y_{i',i}$, $y_{ii',i}$,… functions used by unit i which come from other units, function coming from environment is represented as $y_{0,i}$.

Two kinds of imaginary units are introduced in this theorem; one is junction other is branching point. Junction collects the exergetic flows from other units and it delivers them as a unique flow. Conversely, branching point distributes one flow to others. Missions of a junction and a branching point are illustrated in Figure 5.2.



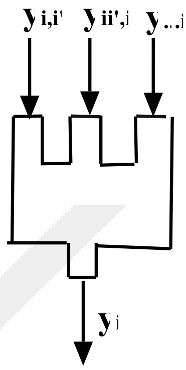


Figure 5.2 **(a)** Branching point **(b)** Junction

Following equations related with these fictitious units will be useful to draw functional diagram.

For a junction; $$\sum_{i'=0}^{n'} y_{i',i} = y_i \quad (5.11)$$

For a branching point; $$y_i = \sum_{i'=0}^{n'} y_{i,i'} \quad (5.12)$$

Two main activities are necessary for functional analysis; Firstly, functions of the system as a whole and each unit are identified then functional diagram is drawn.

If a system is identified in simplest way, one can say the combination of equipments, benefits and losses simply. The operation assesment of an energy system depends on the construction and operation of the system equipments. Therefore, the benefits and losses must be appropriately detected as economic values. Even if this is a difficult duty, it is tried to achieve as much as possible. An economic function with these requirements is defined as,

$$C = \sum_i Z_i + \sum_i C_{0,i} - \sum_i C_{i,0} \quad (5.13)$$

In Equation (5.13), the first term expresses the capital cost of the system comprising fixed charges, maintenance, second term expresses costs of resources and services provided to the system by the environment and third term expresses benefits from products of the system to the environment. The terms of Equation (5.13) are integrated over time and a steady-state operation is presumed,

$$\dot{C} = \sum_i \dot{Z}_i + \sum_i \dot{C}_{0,i} - \sum_i \dot{C}_{i,0} \quad (5.14)$$

Terms of Equation (5.13) and (5.14) can be represented as in monetary units or in physical units, this case is known as ''physical economics''.

Functional analysis identfies all costs as mathematical functions of certain desicion variables which qualify the construction and operation of units and of the quantities purchased or sold,

$$\dot{Z}_i = Z_i(x_i, y_i) = Z_i \quad (5.15)$$

$$\dot{C}_{0,i} = C_{0,i}\left(y_{0,i}\right) = C_{0,i} \quad (5.16)$$

$$\dot{C}_{i,0} = C_{i,0}\left(y_{i,0}\right) = C_{i,0} \quad (5.17)$$

$$\dot{C} = C(x,y) = C \quad (5.18)$$

Equations from (5.15) to (5.18) represent cost rate on both sides, however cost rate quantity itself (e.g. $\dot{C}_{0,i}$) is symbolized on the left hand side, mathematical functional operation which demonstrates its numerical value (e.g. $C_{0,i}$) is represented on the right hand side. Then Equation (5.14) is written as,

$$C\,(x,y) = \sum_i Z_i\,(x, y_i) + \sum_i C_{0,i}\left(y_{i,0}\right) - \sum_i C_{i,0}\left(y_{i,0}\right) \quad (5.19)$$

Mathematical functions for the system units are obtained by technical analysis, they provide the input to a unit as a function of the unique product of the unit and its desicion variables,

$$y_{i,i'} = Y_{i,i'}\left(x_{i'}, y_{i'}\right) = Y_{i,i'} \tag{5.20}$$

Interrelation of the units and the environment is formulated as,

$$y_i = \sum_{i'=0} y_{i,i'} \tag{5.21}$$

Quantitatively fixed product of the system is represented as,

$$y_{i,0} = \hat{y}_{i,0} \tag{5.22}$$

$\hat{y}_{i,0}$, is the fixed quantity of the specified product for example electric power or thermal power.

Fundamental Equations from (5.14) to (5.22) are used to detect unit exergoeconomic costs of the products-functions for optimization. Also it is necessary to write a cost balance equation for each unit,

$$C_i = Z_i + \sum_{i'=0} c_{i'} y_{i',i} = c_i y_i \tag{5.23}$$

Equation (5.23) is solved for each unit, and unit exergoeconnomic costs are derived. For branching points this equation is not taken into consideration because branching point does not have any effect on costs, however junction affects cost only with its function, it does not have any capital cost.

5.8.3 Functional Optimization

Optimization objective for minimization of the total cost is selected as Equation (5.13), (5.14) or (5.19) so Equation (5.19) is selected as objective function,

$$\min C = \sum_i Z_i\,(x, y_i) + \sum_i C_{0,i}\left(y_{i,0}\right) - \sum_i C_{i,0}\left(y_{i,0}\right) \tag{5.24}$$

Equations (5.20) and (5.21) are equality constraints for this objective function.To solve the optimization problem Lagrange multiplier method is used because it is thought useful for problems having much equality constraints.The Lagrangian is performed as,

$$L = \sum_{i} Z_i + \sum_{i} C_{0,i} - \sum_{i} C_{i,0} + \sum_{i'} \sum_{i} \lambda_{i,i'} (Y_{i,i'} - y_{i,i'}) + \sum_{i} \lambda_i \sum_{i'} (y_{i,i'} - y_i) \tag{5.25}$$

For an extremum rate first order conditions are,

$$\nabla_x L(x,y,\lambda) = 0 \tag{5.26}$$

$$\nabla_y L(x,y,\lambda) = 0 \tag{5.27}$$

$$\nabla_\lambda L(x,y,\lambda) = 0 \tag{5.28}$$

Especially, the conditions

$$\frac{\partial L}{\partial y_{i,i'}} = 0 \tag{5.29}$$

In fact Equation (5.29) is a part of Equation (5.27), implemented on Equation (5.22) yields,

$$\lambda_{i,i'} = \lambda_i \tag{5.30}$$

Lagrange multiplier $\lambda_{i,i'}$ joined with an input $y_{i,i'}$ is equal to the Lagrange multiplier λ_i joined with an output y_i, which ensures the $y_{i,i'}$. For this reason Lagrangian is written in a suitable form,

$$L = \sum_{i} (C_i - \lambda_i y_i) + \sum_{i} \left(C_{0,i} - \lambda_{0,i} y_{0,i}\right) - \sum_{i} (C_{i,0} - \lambda_{i,0} y_{i,0}) \tag{5.31}$$

where

$$C_i = Z_i + \sum_{i'} \lambda_{i',i} Y_{i',i} \tag{5.32}$$

Equations from (5.26) to (5.28) are implemented on Equation (5.31) and results are,

$$\nabla_x \sum_{i} C_i = 0 \tag{5.33}$$

$$\lambda_i = \frac{\partial C_i}{\partial y_i} \tag{5.34}$$

$$\lambda_{0,i} = \frac{\partial C_{0,i}}{\partial y_{0,i}} \tag{5.35}$$

$$\lambda_{i,0} = \frac{\partial C_{i,0}}{\partial y_{i,0}} \tag{5.36}$$

Equations from (5.33) to (5.36) yield the optimum values of unknown x, y, λ. If a product is numerically fixed, it is not necessary to write the function $C_{i,0}(y_{i,0})$ and corresponding term does not take part in Equation (5.31). If fuel of the system is quantitavely fixed, same conditions are valid.

Equations of (5.32) and (5.33)-(5.36) stress, Lagrange multipliers as economic indicators, each λ appears as mariginal cost of the following function (product) y. Internal economy of the system is also demonstrated by Lagrange multipliers. This explains why the Lagrange multipliers are preferred to solve the optimization problem. The other reason is, this method requires easily dissociation which simplifies the solution of complex optimization problems.

5.9 Engineering Functional Analysis (EFA)

Engineering Functional Analysis is one of the thermoeconomic methodologies developed by von Spakovsky [77,78] for modeling, optimization and analysis of energy systems. Related concepts and informations will be given in next sections.

5.9.1 Concepts

EFA is a formalism for selecting decomposition constraint functions which ensure higher degrees of engineering decentralization. This optimization method includes the following three subdivisions,

i-) Decentralization constraints are employed by definition of extensive decomposition constraints which are selected for the purpose of decreasing the number of constraints. These are needed for approximate solutions of the overall optimization problem, with emphasizing upon the use of the second law quantities.

ii-) Branch and junction units which permit the defining of component units that have but one single purpose or function are used.

iii-) Totally symmetric Lagrange multiplier format is utilized for decomposition that provides a method of particular solutions through the use of approximate Lagrangians.

Any thermoeconomic methodology can be evaluated in two distinct parts; First one is the creation of a mathematical model which demonstrates the thermodynamic and economic behavior or internal economy of the system, second one is the application of an algorithm to solve the model for the optimum. EFA essentially deals with the modeling process in order to provide a coherent picture of the internal economy of the system, as well as the basis for finding its optimum behavior. The general form of the optimization statement, which time is not a consideration, can be expressed as,

$$\text{minimize} \quad \dot{C}_{TOTAL} = \sum_i \dot{Z}_i + \sum_i \dot{C}_{0,i} + \dot{\S} \tag{5.37}$$

$$\text{w.r.t.} \quad x = \{x_i\} \qquad i = 1,\ldots I \tag{5.38}$$

$$\text{subject to} \quad h_j(x, y) = 0 \qquad j = 1,\ldots,J \tag{5.39}$$

$$g_k(x, y) \geq 0 \qquad k = 1,\ldots,K \tag{5.40}$$

$$\text{where} \quad y = \{Y_j\} \qquad j = 1,\ldots,J \tag{5.41}$$

$$\dot{Z} = \dot{Z}(x, y) \tag{5.42}$$

$$\dot{C}_0 = \dot{C}_0(x, y) \tag{5.43}$$

$$\dot{\S} = \text{constant} \tag{5.44}$$

Independent variables (decision, design, operating, etc.) of the model are represented by the x, in the other hand dependent variables (all constraint variables) are represented by y, and inequality and equality constraint functions are presented by h_i, and g_k , respectively.

Equation (5.37) emphasizes the objective function of the optimization and it aims the minimizing the total cost of the system which includes the capital costs of the used equipment (also investment costs, depreciation, maintenance, replacement, etc.) and the fuel costs. Surcharges, $\dot{\S}$, are added to the cost function however they don't affect the optimization since they are constant. A thermoeconomic model is generally developed with a set of equations similar to the above ones. The global characteristics of the model is denoted by Equation (5.37) since it represents the overall objective of the optimization. Furthermore equality and inequality constraints denote the local characteristics of the model. The structure of a thermoeconomic

model is determined by the formulation of the equality constraints. By this way internal economy of the system and quality of the information are achieved. All these efforts aim to formulate internal economy in different ways. However, this structure influences only the local results of the optimization not the global results because there exits only one possible global optimum for the system which depends on the objective function and equality and inequality in the model.
When a method has been developed, an optimization algorithm must be choosen. Lagrangian approach is selected to reach the optimum EFA results since the behaviour of the internal economy is realized at every step during the optimization procedure.

5.9.2 The Thermoeconomic Structure of EFA

An adopted system was explained at the beginning of TFA application. Following equations explain the thermoeconomic EFA structure of this adopted system,

$$\dot{C}_{TOTAL} = \dot{C}_1 + \dot{C}_2 + \dot{C}_3 + \dot{C}_4 + \dot{C}_{12} \qquad (5.45)$$

$$\text{w.r.t.} \quad x = \{x_i\} \qquad i = 1,...\text{Ɨ} \qquad (5.46)$$

subject to

<u>system products</u>

$$h_{Pj} = Y_j - Y_j(x_{Pj}) = 0 \qquad j = 1,....,\text{Ƥ} \qquad (5.47)$$

<u>unit inputs</u>

$$h_i = Y_j - Y_j(x_i, Y_i) = 0 \qquad j = \text{Ƥ} + 1,...., \text{Ƈ} \qquad (5.48)$$

<u>junctions</u>

$$h_{Jm} = Y_{Jm} - \sum_{in=1}^{2} Y_{J+in} = 0 \qquad j = \text{Ƈ} + 1,...\text{Ɉ}, \qquad m = 1,.., \text{Ɉ} \qquad (5.49)$$

<u>branches</u>

$$h_{Bn} = \sum_{out=1}^{2} Y_{Bn\,out} - Y_J = 0 \qquad j = \text{Ɉ} + 1,...\text{Ɓ}, \qquad n = 1,.., \text{Ɓ} \qquad (5.50)$$

Physical limits

$g_k(x, y) \geq 0$ $\qquad k = 1,\ldots, K$ $\qquad$ (5.51)

$\dot{Z}_i = \dot{Z}_i(x, y)$ $\qquad$ i = unit number $\qquad$ (5.52)

$\dot{C}_0 = \dot{C}_0(x_{GE}, Y_{GE})$ $\qquad$ (5.53)

It is seen that Y_{jm}, $Y_{Bn\,out}$ displaces Y_j when the thermoeconomic structure and internal economy are composed. At this point there is no idea about the independent variables, x_i.

Equation (5.39) shows the equality constraints, it can be classified into four groups; products distributed from the system, Equation (5.47) ; each unit function, Equation (5.48); ones related with each junction, Equation (5.49) and ones related with each branch Equation (5.50). The Y quantity in these equations represent output and input exergetic flows, thermal, mechanical, chemical exergy and negentropy relative to the system's internal economy. Additionally, each Y_j corresponding to a unit function has a mathematical function of the independent variables x_i of the unit and its major product Y_i, while each Y_j related with a system product is a function of the independent variable set x_{Pj} alone.

5.9.3 Thermoeconomic Model of EFA

Thermoeconomic structure for EFA is clarified to reach the results and the mathematical equivalent must be developed. General mathematical functions for optimization problem appearing in Equation (5.45) - (5.53) are derived to express the desicion variables of each unit or system product function. The derivations focus on physical model, thermodynamic model and economic model of Ref [78]. These derivations of each unit also associated junctions and branches will be given later. Similar equations are emphasized in the previous optimization method thus these equations are standart characterizations for these types of units and there is no requirement to derive again. Actually, the behaviour of the internal economy and historic data specify these standart forms.

5.9.4 Internal Economy of EFA

The internal economy of the system is determined with the help of the thermoeconomic structure and its corresponding thermoeconomic model represented in the previous section. EFA uses Lagrange multipliers thus the real unit or mariginal costs associated with this thermoeconomic structure and model can be obtained. Objective function and equality constraints are constructed with Lagrangian such as,

$$L = \sum_{i} \dot{Z}_i + \dot{C}_0 - \sum_{j} \lambda_j [Y_j - Y_j(x_{Pj})] - \sum_{j} \lambda_j [Y_j - Y_j(x_i, Y_i)]$$

$$- \sum_{j} \lambda_j \left(Y_{Jm} - \sum_{in=1}^{2} Y_{J+in} \right) - \sum_{j} \lambda_j \left(\sum_{out=1}^{2} Y_{Bn\,out} - Y_J \right) \tag{5.54}$$

Each λ appeared in Equation (5.54) represent a unit or mariginal cost corresponding to each unit and they are the undefined multipliers for Lagrange method.

The optimization of the constrained problem expressed by the Equations (5.45) through (5.53) is converted to unconstrained one owing to Lagrangian method. Actually, system's total cost, Equation (5.45), have to coincide the minimum value of the Lagrangian, Equation (5.54). System's total cost is minimized subjected to its constraints and following system of equations are obtained,

$$\frac{\partial \dot{L}}{\partial x_i} = 0 \tag{5.55}$$

$$\frac{\partial \dot{L}}{\partial Y_j} = 0 \tag{5.56}$$

$$\frac{\partial \dot{L}}{\partial \lambda_j} = 0 \tag{5.57}$$

Equation (5.55) indicates the system of equations resulted in the optimum decision variable set, x. Equations derived from Equation (5.56) are the unit cost equations and Equation (5.60) gives the original system of equality contraints.

Along these equations Equation (5.57) has already exits and (5.55) resulted from the optimization algorithm which we use here. Only Equation (5.56) is needed to derive, eventually mathematical equivalents follow,

$$\frac{\partial \dot{C}_i}{\partial Y_i} = 0 \tag{5.58}$$

<u>Junction unit cost equations</u>

$$\lambda_{jm} = \frac{\partial \dot{C}_{jm}}{\partial Y_{Jm}} = \frac{\dot{C}_{jm}}{Y_{Jm}} = \left(\sum_{in=1}^{2} \lambda_{j+in} \; Y_{J+in} \right) / \; Y_{Jm} \tag{5.59}$$

<u>Branch unit cost equations</u>

$$\lambda_{Bn1} = \lambda_{Bn1} = \lambda_j \tag{5.60}$$

Other unit cost equations are written for the resources bought by the system and system products. It must be known that the preceeding equations are not approximations, all of the system unit cost equations for the internal economy of the thermoeconomic model can be determined explicitly.

EFA method is explained in detail. The optimum values obtained by the application of all these formulations and the comparison of these values with the TFA results will be examined in the results and discussion section.

5.10 Conclusions

In this chapter, we provided general principles and formulation of two thermoeconomic optimization methods: TFA and EFA. The detailed formulation of each method for biogas engine powered cogeneration is provided and applied to an existing system in chapter 6.

CHAPTER 6

RESULTS AND DISCUSSIONS

6.1 Introduction

The comparative thermoeconomic cost-accounting analysis and assessment approaches, including the four methodologies explained in chapter 4, and thermoeconomic optimization methods given in chapter 5 are applied to an existing biogas engine-powered cogeneration system described in chapter 3. The results are obtained and discussed.

6.2 Results of Thermoeconomic Cost Accounting Methodologies

6.2.1 Exergetic Cost Theory (ECT) Results

6.2.1.1 Exergetic Cost Determinations

The exergetic and thermoeconomic definitions of ECT analysis are described in Chapter 4. Firstly, a general matrix describing all flows in the system is defined. Incidence matrix which helped to demonstrate the flows through the system is represented in Table 6.1.

In this theory, there are a number of rules that enable us to reach the results. These rules are set in chapter 4. Rule 1 deals with fuel-product exergy, while Rule 4 provides a description about residue exergy. After the application of Rule 2 and Rule 3, a series of significant equations are obtained and are shown in Table 6.2 and Table 6.3.

Table 6.1 The incidence matrix, and fuel and product matrices representing the biogas engine powered cogeneration system.

↓ Subsystem i	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	$\dot{W}_{GE}$	$\dot{W}_{T}$	$\dot{W}_{P1}$	$\dot{W}_{P2}$	$\dot{W}_{P3}$	$\dot{W}_{P4}$	←Flow Ь
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	0	0	0	1	0	0	0	0	
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	-1	0	0	0	0	
3	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	0	0	0	0	0	1	-1	0	0	0	0	0	0	0	0	0	
4	0	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	0	0	0	0	
5	0	0	1	-1	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
6	0	0	0	0	0	0	0	0	1	-1	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	A
7	0	0	0	0	0	0	0	1	-1	0	0	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
8	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	
9	0	0	0	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	
10	0	0	0	0	0	0	0	0	0	0	-1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	1	
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	-1	0	0	0	0	0	
The system	0	1	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	-1	1	0	0	0	0	0	0	

↓ Subsystem i	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	$\dot{W}_{GE}$	$\dot{W}_{T}$	$\dot{W}_{P1}$	$\dot{W}_{P2}$	$\dot{W}_{P3}$	$\dot{W}_{P4}$	←Flow Ь
1																										1					
2																						1	-1								
3											-1	1																			
4																							1	-1							
5							1	-1																							
6												1	-1																		A_F
7														1	-1																
8																											1				
9																												1			
10																													1		
11																														1	
12																					1										
The system																					1										

↓ Subsystem i	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	$\dot{W}_{GE}$	$\dot{W}_{T}$	$\dot{W}_{P1}$	$\dot{W}_{P2}$	$\dot{W}_{P3}$	$\dot{W}_{P4}$	←Flow Ь
1																			-1	1											
2																										1					
3																				1	-1										
4				-1	1																										
5			-1	1																											
6									-1	1																					A_P
7								-1	1																						
8		-1	1																												
9						-1	1																								
10											1		-1																		
11																-1	1														
12																															
The system		-1			1																				1						

Table 6.2 Auxiliary equations resulting from the application of Rule 2 for Figure 4.2 and Table 4.1.

$\dot{E}x^*_{13}/\dot{E}x_{13}=\dot{E}x^*_{12}/\dot{E}x_{12}$	$\rightarrow\dot{E}x^*_{13}-x_3\dot{E}x^*_{12}=0$	$x_3=\dot{E}x_{13}/\dot{E}x_{12}$
$\dot{E}x^*_{8}/\dot{E}x_{8}=\dot{E}x^*_{9}/\dot{E}x_{9}$	$\rightarrow\dot{E}x^*_{8}-x_5\dot{E}x^*_{9}=0$	$x_5=\dot{E}x_{8}/\dot{E}x_{9}$
$\dot{E}x^*_{15}/\dot{E}x_{15}=\dot{E}x^*_{16}/\dot{E}x_{16}$	$\rightarrow\dot{E}x^*_{15}-x_7\dot{E}x^*_{16}=0$	$x_7=\dot{E}x_{15}/\dot{E}x_{16}$

Table 6.3 Auxiliary equations resulting from the application of Rule 3 for Figure 4.2 and Table 4.1.

$\dot{E}x^*_{11}/\dot{E}x_{11}=\dot{E}x^*_{10}/\dot{E}x_{10}$	$\rightarrow\dot{E}x^*_{11}-x_6\dot{E}x^*_{10}=0$	$x_6=\dot{E}x_{11}/\dot{E}x_{10}$
$\dot{E}x^*_{4}/\dot{E}x_{4}=\dot{E}x^*_{3}/\dot{E}x_{3}$	$\rightarrow\dot{E}x^*_{4}-x_8\dot{E}x^*_{3}=0$	$x_8=\dot{E}x_{4}/\dot{E}x_{3}$
$\dot{E}x^*_{8}/\dot{E}x_{8}=\dot{E}x^*_{7}/\dot{E}x_{7}$	$\rightarrow\dot{E}x^*_{8}-x_9\dot{E}x^*_{7}=0$	$x_9=\dot{E}x_{8}/\dot{E}x_{7}$
$\dot{E}x^*_{12}/\dot{E}x_{12}=\dot{E}x^*_{14}/\dot{E}x_{14}$	$\rightarrow\dot{E}x^*_{12}-x_{10}\dot{E}x^*_{14}=0$	$x_{10}=\dot{E}x_{12}/\dot{E}x_{14}$
$\dot{E}x^*_{18}/\dot{E}x_{18}=\dot{E}x^*_{17}/\dot{E}x_{17}$	$\rightarrow\dot{E}x^*_{18}-x_{11}\dot{E}x^*_{17}=0$	$x_{11}=\dot{E}x_{18}/\dot{E}x_{17}$

A few important points have to be discussed before the calculations. The line 23-24-25 in Figure 4.2 is the exhaust gas line from the engine. Because no more exergy is spent to obtain these flows, their exergetic costs are equal to their exergies, as seen in Table 6.4. Equation (4.6) is used to determine the exergetic costs and unit exergetic costs. Using developed relations from ECT, exergetic costs of flows are calculated and represented in Table 6.4. It is obvious that unit exergetic cost rises during the processes in the system, as more exergy is destroyed to produce the flows. It emphasizes the amount of fuel necessary for each exergetic component, and its value also demonstrates the production process inefficiency. It is understood from Table 6.4 that the unit exergetic costs show high increments up to 4.221 for the electrical work.

Fortunately, hot water flows have small exergy consumptions, which benefits cogeneration. In fact Table 6.4 has various aspects of ECT. One of them is the work given to the pumps that are assumed to be the fuels, so their exergetic costs are equal to their exergy. Flow 20 is the real fuel for the system, which is the air-fuel mixture that naturally has the same exergetic cost as its exergy because air - at dead state - does not have exergy or an exergetic cost.

Table 6.4 Exergetic costs obtained from the solution of equation, $A \times \dot{E}x^{*} = 0$.

Flow No	Exergy $\dot{E}x$ (kW	Exergetic cost $\dot{E}x^{*}$ (kW)	Unit exergetic cost κ^{*}
3	350.900	417.600	1.190
4	352.800	419.688	1.190
5	447.300	670.958	1.500
6	518.700	859.466	1.656
7	391.400	594.666	1.518
8	400.000	607.153	1.518
9	234.300	355.684	1.518
10	285.900	536.450	1.876
11	291.700	547.179	1.876
12	49.8300	50.7260	1.017
13	58.3700	59.0710	1.014
14	47.6700	48.3420	1.014
15	357.700	658.981	1.843
16	259.400	478.216	1.843
17	220.900	784.000	3.549
18	248.700	882.000	3.549
20	4046.40	4046.40	1.000
21	4154.13	4228.60	1.020
22	4136.23	4221.15	1.021
23	374.300	374.300	1.000
24	192.200	192.200	1.000
25	3.69200	3.69200	1.000
$\dot{W}_{GE}$	1000.00	4221.15	4.221
$\dot{W}_{T}$	159.750	182.200	1.140
$\dot{W}_{P1}$	2.08800	2.08800	1.000
$\dot{W}_{P2}$	12.4880	12.4880	1.000
$\dot{W}_{P3}$	3.38400	3.38400	1.000
$\dot{W}_{P4}$	98.0000	98.0000	1.000

After determining the unit exergetic costs of flows, exergetic costs of components should be calculated. The incidence matrix, A, which explicitly shows the inputs and outputs of the cogeneration system is not enough on its own. Therefore, the fuel and product matrices, A_F, and, A_P as seen in Table 6.1, are used to determine the exergetic cost for each component.

To obtain more accurate results from the thermoeconomic analysis, the cost allocation of subsystems and other expenditures are obtained from the plant manager. The operating and maintenance costs are obtained by considering the entire cogeneration economic life, i.e. 25 years from 2006 to 2031. These costs are escalated by using the average nominal escalation rate, which is 5% in US dollars. The average capacity factor (τ) for the entire plant is 91.7%, which means that the system operates at full load for 8030 hours out of the total available 8760 hours per year. The total capital investment in the plant was 1.237 million US dollars. The purchased equipment costs (PEC), the hourly levelized costs of the capital investment (CI), the operating and maintaining (OM) costs, and the total costs of the components of the plant are given in Table 6.5.

Table 6.5 The cost rates associated with the initial capital investment, and the operating and maintenance costs for the components of the biogas engine powered cogeneration.

Component	PEC ($)	$\dot{Z}^{CI}$ ($/h)	$\dot{Z}^{OM}$ ($/h)	$\dot{Z}^{T}$ ($/h)
Compressor	38461.50	0.19100	0.009500	0.2000
Turbine	38461.50	0.19100	0.009500	0.2000
P1	2412.600	0.01200	0.000600	0.0126
P2	1853.100	0.00923	0.000461	0.00969
P3	1573.400	0.00783	0.000391	0.00822
P4	2237.810	0.01110	0.000557	0.01165
Intercooler	17482.50	0.08700	0.000435	0.09135
EGHE	1950.000	0.09750	0.000487	0.10237
HE1	8898.600	0.04432	0.002216	0.04653
HE2	8898.600	0.04432	0.002216	0.04653
LOHE	6993.000	0.03480	4.33×10^{-6}	0.03480
GE	419580.4	2.09000	0.104500	2.19400
System	-	-	-	2.95774

6.2.1.2 Thermoeconomic Cost Balance of ECT for BPCS

The relationship between exergy, exergetic cost, unit exergetic cost and thermoeconomic costs are shown in Figure 6.1. It is obvious that exergetic analysis that must be linked to economics is enough to perform a thermoeconomic cost analysis.

In Figure 6.1, the use of vector products is essential otherwise the calculations will be wrong.

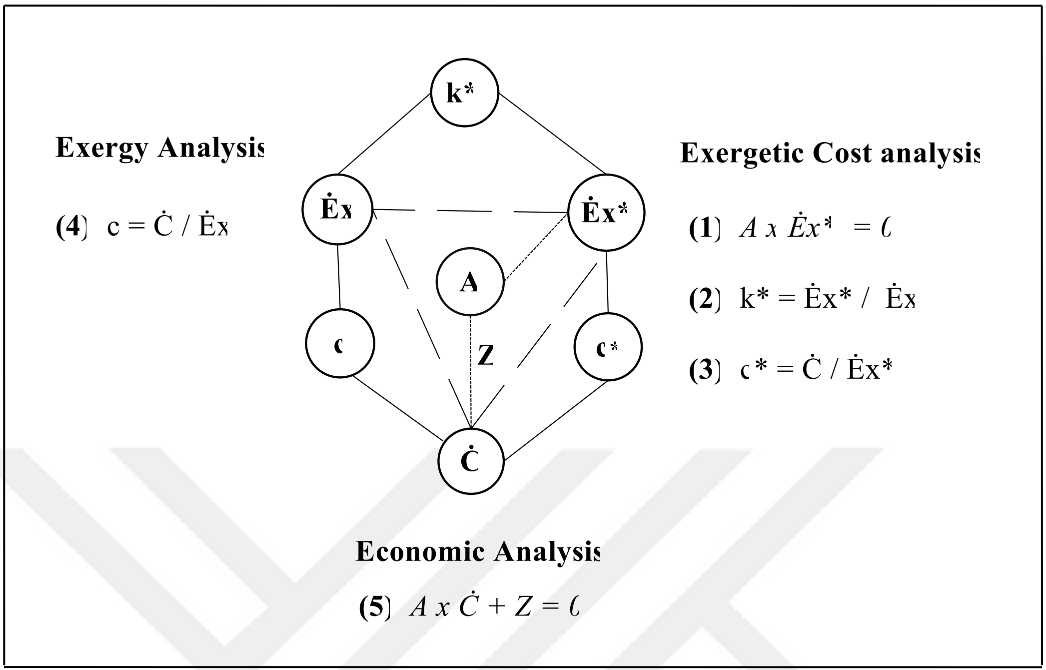


Figure 6.1 Cost hexagon representing the relationships between costs.

In addition, calculated thermoeconomic costs of flows are demostrated in Table 6.6. The unit thermoeconomic cost of the air-fuel mixture is, $c_0 = c_{20} = c^*_{20} = 6.35$ \$/GJ. It is interesting to see the highest thermoeconomic cost belongs to the flow 15, the lubrication oil flow, which is contrary to expectations because thoughts are naturally directed towards the work produced by the gas engine. LOHE is an extra component to transfer the heat from the lubrication oil to the water; therefore the cost of this process becomes expensive. In fact this situation emphasizes that not just exergetic cost, but also the unit thermoeconomic cost plays a role in determining the total cost for each flow and component. Furthermore, it is seen from Table 6.6 that works given to the pumps have lower costs because they are produced in the system. Although significant differences are observed in the thermoeconomic costs of the flows, the unit thermoeconomic costs are more stable in the cogeneration system.

Fuel costs for the components of the system are shown in Table 6.7. Work produced from the turbine results from the utilisation of the exhaust gas line; hence, the exergetic cost of fuel is accepted to be equal to its exergy for this device. The same situation is valid for the EGHE. It also uses exhaust gas as fuel. The compressor uses the turbine work; therefore the turbine product is the compressor's fuel. However, only their exergetic costs are the same; because of exergy destruction not all of the produced work can be applied to the air-gas mixture. This result is concluded from the exergetic calculations during the analysis. The unit thermoeconomic costs of the pumps are known beforehand, and their exergetic costs are equal to their exergy, which was previously remarked upon.

Table 6.6 Cost hexagon results for the system flows in Figure 4.2.

Flow no	Exergy $\dot{E}x$ (kW)	Exergetic cost $\dot{E}x^*$ (kW)	Unit exergetic cost, κ^*	Unit thermoeconomic cost, c^* ($/GJ)	Unit exergoeconomic cost, c ($/GJ)	Thermoeconomic cost $\dot{C}$ ($/h)
3	350.900	417.600	1.190	26.553	31.570	39.8800
4	352.800	419.688	1.190	26.553	31.570	40.0800
5	447.300	670.958	1.500	26.044	39.067	62.9100
6	518.700	859.466	1.656	26.110	43.300	80.8550
7	391.400	594.666	1.518	25.193	38.235	53.8760
8	400.000	607.153	1.518	25.193	38.200	55.0080
9	234.300	355.684	1.518	25.193	38.203	32.2240
10	285.900	536.450	1.876	35.135	65.671	67.5920
11	291.700	547.179	1.876	35.135	65.653	68.9440
12	49.8300	50.7260	1.017	34.553	35.175	6.31000
13	58.3700	60.0000	1.014	32.520	34.292	7.20600
14	47.6700	48.3420	1.014	33.884	34.362	5.89700
15	357.700	658.981	1.843	50.792	93.136	119.934
16	259.400	478.216	1.843	50.792	93.201	87.0350
17	220.900	784.000	3.549	25.031	88.727	70.5600
18	248.700	882.000	3.549	25.031	88.661	79.3800
20	4046.40	4046.40	1.000	6.3500	6.3500	92.5000
21	4154.13	4228.60	1.020	7.0300	7.1560	107.017
22	4136.23	4221.15	1.021	6.9400	7.0820	105.461
23	374.300	374.300	1.000	23.517	23.517	31.6900
24	192.200	192.200	1.000	26.531	26.531	18.3570
25	3.69200	3.69200	1.000	34.985	34.985	0.46500
$\dot{W}_{GE}$	1000.00	4221.15	4.221	7.2430	30.573	110.065
$\dot{W}_{T}$	159.750	182.100	1.140	23.641	23.529	13.5320
$\dot{W}_{P1}$	2.08800	2.08800	1.000	25.000	25.000	0.18800
$\dot{W}_{P2}$	12.4880	12.4880	1.000	25.000	25.000	1.12400
$\dot{W}_{P3}$	3.38400	3.38400	1.000	25.000	25.000	0.30400
$\dot{W}_{P4}$	98.0000	98.0000	1.000	25.000	25.000	8.82000

Table 6.8 illustrates the product cost results of system components. As in the fuel case, the highest thermoeconomic cost belongs to the gas engine. By observing Table

6.8 it is obvious that for component 3, the intercooler, there is a failure because of the job this component is supposed to do. The exergy of the product is greater than the exergy of the fuel, which is impossible according to the exergetic cost theory, but its main purpose is to cool the air-fuel mixture not to heat the water circulating in the closed loop through the HE1. During the application of the theory rules this point must be adressed.

Table 6.7 Fuel cost results of ECT for the components in Figure 4.2.

Component No	Exergy Ėx (kW)	Exergetic cost Ėx^* (kW)	Unit exergetic cost, κ^*	Unit thermoeconomic cost, c^* ($/GJ)	Unit exergoeconomic cost, c ($/GJ)	Thermoeconomic cost Ċ ($/h)
1	159.75	182.100	1.139	20.641	23.529	13.532
2	182.10	182.100	1.000	20.336	20.336	13.332
3	8.5400	9.27400	1.121	26.807	29.111	0.8950
4	188.50	188.508	1.000	26.364	26.364	17.892
5	165.70	251.470	1.517	25.167	38.194	22.784
6	10.700	10.7290	1.002	33.890	33.982	1.3090
7	98.300	180.766	1.838	50.554	92.966	32.899
8	2.0880	2.08800	1.000	25.000	25.000	0.1880
9	12.488	12.4880	1.000	25.000	25.000	1.1240
10	3.3840	3.38400	1.000	25.000	25.000	0.3040
11	98.000	98.0000	1.000	25.000	25.000	8.8200
12	4136.2	4221.155	1.020	6.9390	7.0820	105.46

Table 6.8 Product cost results of ECT for the components in Figure 4.2.

Component No	Exergy Ėx (kW)	Exergetic cost Ėx^* (kW)	Unit exergetic cost, κ^*	Unit thermoeconomic cost, c^* ($/GJ)	Unit exergoeconomic cost, c ($/GJ)	Thermoeconomic cost Ċ ($/h)
1	107.73	182.100	1.690	22.144	37.431	14.517
2	159.75	182.100	1.139	20.641	23.529	13.532
3	17.900	9.27400	2.437	46.605	24.146	1.5560
4	71.400	188.508	2.640	39.755	104.96	26.979
5	94.500	251.470	2.661	25.218	67.107	22.830
6	5.8000	10.7290	1.849	35.003	64.750	1.3520
7	51.600	180.766	3.503	54.348	190.39	35.368
8	1.9000	2.08800	1.098	26.607	29.239	0.2000
9	8.6000	12.4880	1.452	25.179	36.563	1.1320
10	3.3000	3.38400	1.025	36.117	37.037	0.4400
11	27.800	98.0000	3.525	25.000	88.129	8.8200
12	1000.0	4221.15	4.221	7.0550	29.783	107.22

The end result of the exergetic cost theory, cost of the gas engine work flow is specified in Table 6.9.

Table 6.9 Costs of work produced by the biogas engine according to the ECT.

Component	Cost of Work Produced by Biogas Engine	
	Unit exergoeconomic cost c_W (\$/GJ)	Thermoeconomic cost $\dot{C}_W$ (\$/h)
Gas Engine	30.573	110.065

6.2.2 Modified Productive Structure Analysis (MOPSA) Results

6.2.2.1 Exergetic Balance of MOPSA for BPCS

This method evaluates the streams flowing through the system by separating them thermally and mechanically. Exergetic balances and cost calculations are performed according to this perspective. Table 6.10 shows thermal and mechanical exergy flow rates also entropy flow rates at various state points shown in Figure 4.2. These flow rates are calculated based on the values of measured properties such as pressure, temperature and the mass flow rate at various points (see Table 4.1).

Various exergy flow rates passing the boundary of each unit in the cogeneration system are presented in Table 6.11. Positive values of exergies show the product exergy flow rate, on the other hand negative values indicate the resource flow rate or fuel. In this situation, the product of the unit is the added exergy while the source is consumed. Entropy produced in each component is assumed to be the product of the exergy balance equation. Summation of the exergy flow rates of resources and products is equal to zero for each unit and for the total system. This zero sum shows that exergy balances have been perfectly executed.

Table 6.10 Property values, thermal and mechanical exergy flows and entropy production rates at various state points in the biogas engine powered cogeneration system.

State No	Fluid	Pressure P (bar)	Temperature T (°C)	Mass flow rate $\dot{m}$ (kg/sn)	Entropy generation $\dot{S}$ (kW/K)	Thermal exergy $\dot{E}x^T$ (kW)	Mechanical exergy $\dot{E}x^M$ (kW)
0	Air	1.00	25.00	-	-	0.0000	0.000
0’	Water	1.00	25.00	-	-	0.0000	0.000
0’’	Biogas	1.00	25.00	-	-	---	---
0’’’	Lub oil	1.00	25.00	-	-	0.0000	0.000
2	Biogas	1.02	30.10	0.129	1.5010	0.0130	0.390
3	Water	5.25	75.80	20.88	21.402	342.00	8.890
4	Water	6.20	75.80	20.88	21.402	341.90	10.89
5	Water	6.10	82.80	20.88	23.135	436.60	10.68
6	Water	3.40	88.00	20.88	24.408	513.60	5.020
7	Water	2.80	88.40	15.61	18.326	388.60	2.810
8	Water	7.60	88.50	15.61	18.341	389.70	10.30
9	Water	7.50	72.40	15.61	15.355	224.10	10.17
10	Water	7.30	77.90	15.61	16.390	276.00	9.860
11	Water	7.20	78.50	15.61	16.490	282.00	9.700
12	Water	4.55	50.00	11.28	7.9350	47.000	2.830
13	Water	4.50	52.10	11.28	8.2400	55.370	3.000
14	Water	1.10	50.00	11.28	7.9370	47.490	0.180
15	Lub oil	4.69	100.6	20.00	12.542	349.40	8.337
16	Lub oil	4.50	89.00	20.00	11.158	251.50	7.908
17	Lub oil	1.00	85.00	20.00	10.676	220.90	0.000
18	Lub oil	6.90	87.00	20.00	10.918	235.40	13.33
19	Air	1.00	25.00	1.387	7.9040	0.0000	0.000
20	Air-fuel	1.00	25.00	1.500	9.3110	0.0000	0.000
21	Air-fuel	1.90	116.9	1.500	9.4690	20.059	88.06
22	Air-fuel	1.90	51.00	1.500	9.1550	1.7710	88.06
23	Exhaust gas	2.40	460.0	1.500	9.5620	262.00	112.3
24	Exhaust gas	1.17	360.6	1.500	9.6370	172.10	20.15
25	Exhaust gas	1.00	65.00	1.500	8.7390	3.6920	0.000

Table 6.11 Exergy balances for each component in the system of Figure 4.2 according to the MOPSA.

Component	$\dot{E}x^{W}$ (kW)	$\dot{E}x^{T}$ (kW)	$\dot{E}x^{M}$ (kW)	$\dot{S}$ (kW/K)	$\dot{E}x^{CHE}$ (kW)
Compressor	-155.00	20.059	88.0600	46.78600	0.0000
Turbine	159.75	-90.900	-92.1500	23.30000	0.0000
Intercooler	0.0000	-10.218	-1.01000	11.27900	0.0000
EGHE	0.0000	-13.900	-97.8100	117.7100	0.0000
HE1	0.0000	-70.900	-0.34000	71.24000	0.0000
HE2	0.0000	-2.0000	-2.98000	4.980000	0.0000
LOHE	0.0000	-46.000	-0.73900	46.73900	0.0000
P1	-2.0880	0.0880	2.00000	0.000000	0.0000
P2	-12.488	1.1000	7.49000	4.186000	0.0000
P3	-3.3840	0.0100	3.38300	0.000000	0.0000
P4	-98.000	14.500	13.3300	70.17000	0.0000
GE	1000.0	-260.229	-24.2400	3330.869	-4046.4
BPCS	888.79	-458.566	-105.006	3727.259	-4046.4

6.2.2.2 Thermoeconomic Cost Balance Equations Based on MOPSA for BPCS

The general cost balance equation is given in Equation (4.29) for MOPSA. Then for each component in our cogeneration system, shown in Figure 4.2, cost balance equations can be derived. When the cost balance equation is used for a component, a new unit cost must be attributed to the component's principal product [50], whose unit cost is expressed in bold. After the unit cost is assigned to the main product of the components, the cost balance equations for the system are formulated.

(1) Compressor

$$\left(\dot{E}x_{20}^{T} - \dot{E}x_{21}^{T}\right)c_T + \left(\dot{E}x_{20}^{M} - \dot{E}x_{21}^{M}\right)\mathbf{c_{1M}} + T_0\left(\dot{S}_{20} - \dot{S}_{21}\right)c_S + \dot{Z}_1 = \dot{W}_C c_{W_T} \quad (6.1)$$

(2) Turbine

$$\left(\dot{E}x_{23}^{T} - \dot{E}x_{24}^{T}\right)c_T + \left(\dot{E}x_{23}^{M} - \dot{E}x_{24}^{M}\right)c_M + T_0\left(\dot{S}_{20} - \dot{S}_{21}\right)c_S + \dot{Z}_2 = \dot{W}_T \mathbf{c_{W_T}} \quad (6.2)$$

(3) Intercooler

$$\left(\dot{E}x_{21}^{T} - \dot{E}x_{22}^{T}\right)\mathbf{c_{3T}} + \left(\dot{E}x_{21}^{M} - \dot{E}x_{22}^{M}\right)c_M + \left(\dot{E}x_{12}^{T} - \dot{E}x_{13}^{T}\right)d_T + \left(\dot{E}x_{12}^{M} - \dot{E}x_{13}^{M}\right)d_M +$$

$$T_0\left(\dot{S}_{21} - \dot{S}_{22} + \dot{S}_{12} - \dot{S}_{13} + \dot{Q}_3 / T_0\right)c_S + \dot{Z}_3 = 0 \quad (6.3)$$

(4) EGHE

$$\left(\dot{E}x_5^T - \dot{E}x_6^T\right)\mathbf{d_{4T}} + \left(\dot{E}x_5^T - \dot{E}x_6^T\right)d_M + \left(\dot{E}x_{24}^T - \dot{E}x_{25}^T\right)c_T + \left(\dot{E}x_{24}^M - \dot{E}x_{25}^M\right)c_M + T_0\left(\dot{S}_{24} - \dot{S}_{25} + \dot{S}_5 - \dot{S}_6 + \dot{Q}_4 / T_0\right)c_S + \dot{Z}_4 = 0 \tag{6.4}$$

5) HE-1

$$\left(\dot{E}x_4^T - \dot{E}x_5^T\right)\mathbf{d_{5T}} + \left(\dot{E}x_8^T - \dot{E}x_9^T\right)d_T + \left(\dot{E}x_4^M - \dot{E}x_5^M + \dot{E}x_8^M - \dot{E}x_9^M\right)d_M + T_0\left(\dot{S}_4 - \dot{S}_5 + \dot{S}_8 - \dot{S}_9 + \dot{Q}_5 / T_0\right)c_S + \dot{Z}_5 = 0 \tag{6.5}$$

6) HE-2

$$\left(\dot{E}x_{10}^T - \dot{E}x_{11}^T\right)\mathbf{d_{6T}} + \left(\dot{E}x_{13}^T - \dot{E}x_{14}^T\right)d_T + \left(\dot{E}x_{10}^M - \dot{E}x_{11}^M + \dot{E}x_{13}^M - \dot{E}x_{14}^M\right)d_M + T_0\left(\dot{S}_{10} - \dot{S}_{11} + \dot{S}_{13} - \dot{S}_{14} + \dot{Q}_6 / T_0\right)c_S + \dot{Z}_6 = 0 \tag{6.6}$$

7) LOHE

$$\left(\dot{E}x_9^T - \dot{E}x_{10}^T\right)\mathbf{d_{7T}} + \left(\dot{E}x_{15}^T - \dot{E}x_{16}^T\right)d_T + \left(\dot{E}x_9^M - \dot{E}x_{10}^M + \dot{E}x_{15}^M - \dot{E}x_{16}^M\right)d_M + T_0\left(\dot{S}_9 - \dot{S}_{10} + \dot{S}_{15} - \dot{S}_{16} + \dot{Q}_7 / T_0\right)c_S + \dot{Z}_7 = 0 \tag{6.7}$$

8) P-1

$$\left(\dot{E}x_3^T - \dot{E}x_4^T\right)d_T + \left(\dot{E}x_3^M - \dot{E}x_4^M\right)\mathbf{d_{8M}} + T_0\left(\dot{S}_3 - \dot{S}_4\right)c_S + \dot{Z}_8 = \dot{W}_{P1}d_w \tag{6.8}$$

9) P-2

$$\left(\dot{E}x_7^T - \dot{E}x_8^T\right)d_T + \left(\dot{E}x_7^M - \dot{E}x_8^M\right)\mathbf{d_{9M}} + T_0\left(\dot{S}_8 - \dot{S}_9\right)c_S + \dot{Z}_9 = \dot{W}_{P2}d_w \tag{6.9}$$

10) P-3

$$\left(\dot{E}x_{14}^T - \dot{E}x_{12}^T\right)d_T + \left(\dot{E}x_{14}^M - \dot{E}x_{12}^M\right)\mathbf{d_{10M}} + T_0\left(\dot{S}_{14} - \dot{S}_{12}\right)c_S + \dot{Z}_{10} = \dot{W}_{P3}d_w \tag{6.10}$$

11) P-4

$$\left(\dot{E}x_{17}^T - \dot{E}x_{18}^T\right)d_T + \left(\dot{E}x_{17}^M - \dot{E}x_{18}^M\right)\mathbf{d_{11M}} + T_0\left(\dot{S}_{17} - \dot{S}_{18}\right)c_S + \dot{Z}_{11} = \dot{W}_{P4}d_w \tag{6.11}$$

12) GE

$$\dot{E}x^{CHE}c_0 + \left(\dot{E}x_{22}^T - \dot{E}x_{23}^T\right)c_T + \left(\dot{E}x_{22}^M - \dot{E}x_{23}^M\right)c_M + \left(\dot{E}x_{11}^T - \dot{E}x_7^T + \dot{E}x_{18}^T - \dot{E}x_{15}^T\right)d_T + \left(\dot{E}x_{11}^M - \dot{E}x_7^M + \dot{E}x_{18}^M - \dot{E}x_{15}^M\right)d_M + T_0\left(\dot{S}_{22} - \dot{S}_{23} + \dot{S}_{11} - \dot{S}_7 + \dot{S}_{18} - \dot{S}_{15} + \dot{Q}_{12} / T_0\right)c_S + \dot{Z}_{12} = \dot{W}_{GE}\mathbf{c_w} \tag{6.12}$$

Both gas and water exergy streams pass through three components in the cogeneration system. Inlet and outlet flows are highlighted in Equations (6.3) and (6.4). Significant pressure changes don’t occur in the heat exchangers but considerable heat losses must be taken into account, as the series of equations from (6.3) to (6.7) emphasize. These instructions are necessary to formulate the complete exergy and cost balances for the system. Twelve cost balance equations from twelve units of the plant are reproduced with 17 unknown unit exergoeconomic costs c_{1M}, c_{W_T}, c_{3T}, d_{4T}, d_{5T}, d_{6T}, d_{7T}, d_{8M}, d_{9M}, d_{10M}, d_{11M}, c_w, c_T, c_M, c_S, d_T and d_M. Five more cost balance equations can be obtained for the junctions of thermal and mechanical exergies of the gas and water streams.

Gas streams

$$\left(\dot{E}x_{21}^T - \dot{E}x_{22}^T\right)c_{3T} = \left(\dot{E}x_{21}^T - \dot{E}x_{22}^T\right)c_T \qquad c_{3T} = c_T \tag{6.13}$$

$$\left(\dot{E}x_{20}^M - \dot{E}x_{21}^M\right)c_{1M} = \left(\dot{E}x_{20}^M - \dot{E}x_{21}^M\right)c_M \qquad c_{1M} = c_M \tag{6.14}$$

Water streams

$$\left(\dot{E}x_5^T - \dot{E}x_6^T\right)d_{4T} + \left(\dot{E}x_4^T - \dot{E}x_5^T\right)d_{5T} + \left(\dot{E}x_{10}^T - \dot{E}x_{11}^T\right)d_{6T} + \left(\dot{E}x_9^T - \dot{E}x_{10}^T\right)d_{7T} =$$
$$\left(-\dot{E}x_6^T + \dot{E}x_4^T - \dot{E}x_{11}^T + \dot{E}x_9^T\right)d_T \tag{6.15}$$

$$\left(\dot{E}x_3^M - \dot{E}x_4^M\right)d_{8M} + \left(\dot{E}x_7^M - \dot{E}x_8^M\right)d_{9M} + \left(\dot{E}x_{14}^M - \dot{E}x_{12}^M\right)d_{10M} + \left(\dot{E}x_{17}^M - \dot{E}x_{18}^M\right)d_{11M} =$$
$$\left(\dot{E}x_3^M - \dot{E}x_4^M + \dot{E}x_7^M - \dot{E}x_8^M + \dot{E}x_{14}^M - \dot{E}x_{12}^M + \dot{E}x_{17}^M - \dot{E}x_{18}^M\right)d_M \tag{6.16}$$

Another cost balance equation suitable for the exergy balance for the boundary of the system can be expressed as follows,

$$\left(\dot{E}x_{20}^T - \dot{E}x_{25}^T\right)c_T + \left(\dot{E}x_{20}^M - \dot{E}x_{25}^M\right)c_M + \left(\dot{E}x_3^T - \dot{E}x_6^T\right)d_T + \left(\dot{E}x_3^M - \dot{E}x_6^M\right)d_M +$$
$$T_0\left(\dot{S}_{20} - \dot{S}_{25} + \dot{S}_3 - \dot{S}_6\right)c_S + \dot{Z}_{bound} = 0 \tag{6.17}$$

$\dot{Z}_{bound}$ is the plant construction cost, which is one-third or two-thirds of the equipment costs. In these calculations it is taken to be one-third of the total cogeneration. When configuring all these formulas, it is important to emphasize that unit cost that defines the aim of the component additionally different unit costs are assigned depending on the type of fluids. However entropy generation acts in the same way everywhere, so its unit cost is unique.

Table 6.12 denotes the cost flow rates corresponding to the subsystems' exergy flow rates and the construction costs. The unit exergoeconomic cost of biogas is 6.350 \$/GJ which is demonstrated before. The same sign order for the products and resources' cost flow rates is found, which is used to define the exergy balances in Table 6.11. Entropy generation cost in a component shows the consumed cost. The summation of the cost flow rates for each unit in the system is equal to zero satisfying true cost balances.

Table 6.12 Cost flow rates for each component in the system of Figure 4.2 according to the MOPSA.

Component	$\dot{C}_W$ or $\dot{D}_W$ (\$/h)	$\dot{C}_T$ (\$/h)	$\dot{C}_M$ (\$/h)	$\dot{D}_T$ (\$/h)	$\dot{D}_M$ (\$/h)	$\dot{C}_0$ (\$/h)	$\dot{C}_S$ (\$/h)	$\dot{Z}$ (\$/h)
Compressor	- 17.1070	0.034	17.340	0.000000	0.0000	0.000	-0.0670	-0.2000
Turbine	17.390	-0.154	-17.004	0.000000	0.0000	0.000	-0.0320	-0.2000
Intercooler	0.0000	0.038	0.0000	0.113000	- 0.0227	0.000	-0.0386	-0.0900
EGHE	0.0000	0.430	-3.0420	5.238000	- 2.2580	0.000	-0.2660	-0.1020
HE1	0.0000	0.000	0.0000	0.364000	- 0.1480	0.000	-0.1700	-0.0460
HE2	0.0000	0.000	0.0000	1.274000	- 1.2150	0.000	-0.0130	-0.0460
LOHE	0.0000	0.000	0.0000	0.445000	- 0.2940	0.000	-0.1170	-0.0340
P1	- 0.1870	0.000	0.0000	0.001850	0.1977	0.000	0.000	-0.0126
P2	- 1.1230	0.000	0.0000	0.020300	1.1223	0.000	-0.0100	-0.0096
P3	- 0.3040	0.000	0.0000	0.000185	0.3120	0.000	0.000	-0.0082
P4	- 8.8200	0.000	0.0000	0.268200	8.7312	0.000	-0.1684	-0.0110
GE	85.536	0.442	4.7100	0.957000	4.7050	-92.50	-1.6560	-2.1940
Boundary	0.0000	0.010	0.0000	3.182000	1.5440	0.000	-2.8120	-1.9140
System	75.385	0.800	2.0040	12.49100	12.674	-92.50	-5.3500	-4.8770

At the end of the MOPSA calculations, pump 4 indicates a high mechanical thermoeconomic cost in Table 6.12, which means the inverse of the exergetic cost theory is not profitable. It is obvious that using exhaust gas to heat the water through the EGHE does not seem advantangeous. Finally, the cost of the gas engine work flow, according to the modified productive structure analysis, is given in Table 6.13.

Table 6.13 Costs of work produced by the biogas engine powered cogeneration according to the MOPSA.

	Cost of Work Produced by Biogas Engine Powered Cogeneration	
Component	Unit Exergoeconomic cost c_W (\$/GJ)	Thermoeconomic cost $\dot{C}_W$(\$/h)
Gas Engine	23.760	85.536

Table 6.13 indicates that the MOPSA cost results are smaller than the results obtained from the ECT analysis.

6.2.3 Wonergy Results

6.2.3.1 Energy and Exergy Balances of Wonergy for BPCS

Wonergy emphasize the first law of thermodynamics which is the energy balance equation for the i-th component and overall system as Equation (4.30) and (4.31). The tabulated values of these energy equations are listed in Table 6.14.

Table 6.14 The energy balance of the biogas engine powered cogeneration according to the Wonergy method.

Component	$\dot{W}$ (kW)	$\dot{E}_Q$ (kW)	E_F^{CHE} (kW)	$\dot{E}_F$ (kW)	$\dot{E}_P$ (kW)	$\dot{E}_L$ (kW)
Compressor	-155.21	-	-	-	-155.210	-
Turbinne	159.75	-	-	159.750	-	-
Intercooler	-	-	-	99.2600	-99.0000	0.26000
EGHE	-	-	-	456.160	451.000	5.16000
HE1	-	-	-	1055.27	-611.850	443.420
HE2	-	39	-	103.000	-	64.0000
LOHE				512.000	-360.000	152.000
P1	-2.0880	-	-	-	-2.08800	-
P2	-12.488	-	-	-	-12.4880	-
P3	-3.3840	-	-	-	-3.38400	-
P4	-98.000	-	-	-	-98.0000	-
GE	1000.0	-	2308.06	-	-592.420	715.640
System	888.58	39	2308.06	2385.44	-2385.44	1380.48

The exergy balance equation for the i-th component and overall system is represented in Table 6.15 that shows the values of each the terms in Equations (4.32) and (4.33).

It is obvious from the Wonergy equations, Equation (4.34) and (4.35) also from Table 6.14 and Table 6.15, that the summation of $\dot{K}_{F,i}$ and $\dot{K}_{P,i}$ for all components is exactly zero.

This method divided the system components into three classes according to their tasks; the common components [$\mathbb{C}$] associated with work and heat production, the work-only components [W] associated with work production, and the heat-only components [Q] associated with heat production. According to these classifications, the common components are HE1, P1, P2, P3 and P4; the work-only components are the compressor, the turbine, the gas engine, the EGHE, the LOHE, and the heat-only component is the HE2 in the biogas engine powered cogeneration system. Here, the EGHE can be a common component or a work component; however, our system is part of a wastewater treatment plant where it is more reasonable that the EGHE contributes to work.

Table 6.15 The exergy balance of the biogas engine powered cogeneration system according to the Wonergy method.

Component	$\dot{W}$ (kW)	$\dot{E}x_Q$ (kW)	Ex_F^{CHE} (kW)	$\dot{E}x_F$ (kW)	$\dot{E}x_P$ (kW)	$\dot{E}x_L$ (kW)
Compressor	-155.21	-	-		-107.730	47.4800
Turbine	159.75	-	-	182.050		22.3000
Intercooler	-	-	-	17.9000	-8.24100	9.65000
EGHE	-	-	-	188.505	-71.4000	117.105
HE1	-	-	-	165.700	-94.5000	71.2000
HE2	-	5.8	-	10.8400	-	5.04000
LOHE	-	-	-	98.3000	-51.6000	46.7000
P1	-2.0880	-	-	-	-2.08800	-
P2	-12.488	-	-	-	-12.4880	-
P3	-3.3840	-	-	-	-3.38400	-
P4	-98.000	-	-	-	-98.0000	-
GE	1000.0	-	4046.4	-	-213.700	2832.655
System	888.58	5.8	4046.4	663.345	-663.345	-3152.02

6.2.3.2 Thermoeconomic Cost Balance of Wonergy for BPCS

Application of Equation (4.37) to the system requires to reach the thermoeconomic cost allocation for the components which exposed to classifications as mentioned above. Results are provived in Table 6.16

Table 6.16 Cost allocations for biogas engine powered cogeneration using the Wonergy method.

Component	$\dot{K}$ (kW)	$\dot{W}$,$\dot{Q}$ (kW)	k%	$\dot{C}_0$ ($/h)	$\dot{Z}_{ID}$ ($/h)	$\dot{Z}$ ($/h)	c ($/GJ)	$\dot{C}$ ($/h)
Common [₵]	-35.11	-	-	-	0	0.133	94.2220	-
Workonly [W]	24.27	888.58	2.7310	92.451	0	0.491	20.1380	64.419
Heat only [Q]	10.84	39.000	27.794	-	0	0.046	202.542	28.436

Numerical values used in wonergetic calculations include; the heat input of the biogas, $\dot{E}_F^{CHE}$, of 2308.06 kW, the total electricity product, $\dot{W}$, of 888.58 kW, and the heat product, $\dot{E}_Q$, of 39 kW. As understood from Table 6.16, producing work is much more expensive than producing heat because the amount of Wonergy input for work is greater than heat. Of course this is the normal situation for cogeneration systems since heat is a by-product.

At the end of the Wonergy analysis, the cost of the work flow produced by the biogas engine powered cogeneration is shown in Table 6.17.

Table 6.17 Costs of work produced by the biogas engine powered according to the Wonergy method.

Component	Cost of Work Produced by Biogas Engine	
	Unit Exergoeconomic cost c_w(\$/GJ)	Thermoeconomic cost $\dot{C}_W$(\$/h)
Gas Engine	20.138	72.500

6.2.4 Specific Exergy Costing (SPECO) Results

6.2.4.1 Exergetic Balance of SPECO for BPCS

The specific exergy costing method follows three prcosesses to get consequences. Firstly, energy and exergy flows through the system components are identified. Here is exactly calculated energy and exergy for each state of the flows are given in Table 4.1. Secondly, the fuel and product of each component in the system should be defined as in Table 4.2. SPECO confirms that all of these features can establish the exergetic balance of the system and exergetic cost balance is represented in Table 6.17.

6.2.4.2 Thermoeconomic Cost Equations of SPECO for BPCS

Table 6.17 leads to the formulation of Table 6.18. The costs of flows through the system are calculated and the results are given in Table 6.19. Unit exergoeconomic costs of work flows belonging to pumps are assumed to be known, thus it is easy to find their thermoeconomic costs.

Table 6.18 Exergetic cost balances and corresponding auxiliary equations for the components in Figure 4.1.

Component	Cost balance equation	Auxiliary equation
Compressor	$c_{20}\dot{E}x_{20} - c_{21}\dot{E}x_{21} + c_e\dot{W}_C + \dot{Z}_1 = 0$	$c_{20} = 6.35\ \frac{\$}{GJ}$
Turbine	$c_{23}\dot{E}x_{23} - c_{24}\dot{E}x_{24} - c_e\dot{W}_T + \dot{Z}_2 = 0$	$c_{23} = c_{24}$
Intercooler	$c_{21}\dot{E}x_{21} - c_{22}\dot{E}x_{22} + c_{12}\dot{E}x_{12} - c_{13}\dot{E}x_{13} + \dot{Z}_3 = 0$	$c_{21} = c_{22}$
EGHE	$c_{24}\dot{E}x_{24} - c_{25}\dot{E}x_{25} + c_5\dot{E}x_5 - c_6\dot{E}x_6 + \dot{Z}_4 = 0$	$c_{24} = c_{25}$
HE1	$c_8\dot{E}x_8 - c_9\dot{E}x_9 + c_4\dot{E}x_4 - c_5\dot{E}x_5 + \dot{Z}_5 = 0$	$c_8 = c_9$
HE2	$c_{10}\dot{E}x_{10} - c_{11}\dot{E}x_{11} + c_{13}\dot{E}x_{13} - c_{14}\dot{E}x_{14} + \dot{Z}_6 = 0$	$c_{13} = c_{14}$
LOHE	$c_{15}\dot{E}x_{15} - c_{16}\dot{E}x_{16} + c_9\dot{E}x_9 - c_{10}\dot{E}x_{10} + \dot{Z}_7 = 0$	$c_{15} = c_{16} = c_{17}$
P1	$c_3\dot{E}x_3 - c_4\dot{E}x_4 + c_e\dot{W}_{P1} + \dot{Z}_8 = 0$	$c_3 = 31.570\ \frac{\$}{GJ}$
P2	$c_7\dot{E}x_7 - c_8\dot{E}x_8 + c_e\dot{W}_{P2} + \dot{Z}_9 = 0$	-
P3	$c_{14}\dot{E}x_{14} - c_{12}\dot{E}x_{12} + c_e\dot{W}_{P3} + \dot{Z}_{10} = 0$	-
P4	$c_{17}\dot{E}x_{17} - c_{18}\dot{E}x_{18} + c_e\dot{W}_{P4} + \dot{Z}_{11} = 0$	-
GE	$c_{22}\dot{E}x_{22} - c_{23}\dot{E}x_{23} + c_{11}\dot{E}x_{11} - c_7\dot{E}x_7 + c_{18}\dot{E}x_{18} - c_{15}\dot{E}x_{15} - c_W\dot{W} + \dot{Z}_{12} = 0$	$\dot{W}_{GE} = 1000$ kW

Table 6.20 and Table 6.21 illustrate values of fuel and product thermoeconomic costs for each component. It is apparent from the tables that the most expensive unit in the system, according to the SPECO analysis is the gas engine due to the fuel and product prices. The cost of the work flow of the gas engine in SPECO perspective is given in Table 6.22.

Table 6.19 Cost results of the biogas engine powered cogeneration flows according to the SPECO.

Flow No	Exergy $\dot{E}x$ (kW)	Unit exergoeconomic cost, c ($/GJ)	Thermoeconomic cost $\dot{C}$ ($/h)
3	350.900	31.570	39.880
4	352.800	31.550	40.086
5	447.300	40.242	64.894
6	518.700	43.300	80.855
7	391.400	41.660	58.876
8	400.000	41.721	60.078
9	234.300	41.721	35.190
10	285.900	66.111	68.044
11	291.700	65.833	69.314
12	49.8300	34.612	6.2090
13	58.3700	31.661	6.6530
14	47.5300	31.661	5.4170
15	357.700	93.136	119.93
16	259.400	93.136	86.974
17	220.900	93.136	74.065
18	248.700	92.500	173.59
20	4046.40	6.3500	92.500
21	4154.13	7.2110	107.59
22	4136.23	7.2110	107.12
23	374.300	23.517	31.690
24	192.200	23.517	18.357
25	3.69200	23.517	0.4650
$\dot{W}_C$	155.000	27.152	15.150
$\dot{W}_T$	159.750	27.152	15.615
$\dot{W}_{GE}$	1000.00	39.166	141.00
$\dot{W}_{P1}$	2.08800	25.000	0.1880
$\dot{W}_{P2}$	12.4880	25.000	1.1240
$\dot{W}_{P3}$	3.38400	25.000	0.3040
$\dot{W}_{P4}$	98.0000	25.000	8.8200

Table 6.20 Fuel cost results for the components of the biogas engine powered cogeneration system according to the SPECO analysis.

Component	$\dot{E}x_F$ (kW)	Unit Exergoeconomic Cost c ($/GJ)	Thermoeconomic Cost $\dot{C}$ ($/h)
Compressor	155.000	27.152	15.1500
Turbine	182.100	23.517	15.4160
Intercooler	8.54000	14.400	0.44400
EGHE	188.508	26.364	17.8920
HE1	165.700	41.721	24.8880
HE2	10.8400	31.670	1.23600
LOHE	98.3000	26.364	32.9600
P1	2.08800	25.000	0.18800
P2	12.4880	25.000	1.12400
P3	3.38400	25.000	0.30400
P4	98.0000	25.000	8.82000
GE	4136.23	7.2110	107.128

Table 6.21 Product cost results for the components of the biogas engine powered cogeneration system according to the SPECO analysis.

Component	$\dot{E}x_F$ (kW)	Unit Exergoeconomic Cost c ($/GJ)	Thermoeconomic Cost $\dot{C}$ ($/h)
Compressor	107.73	38.910	15.091
Turbine	159.75	27.152	15.615
Intercooler	17.900	7.1840	0.4630
EGHE	71.400	62.095	15.961
HE1	94.500	72.921	24.808
HE2	5.8000	60.823	1.2700
LOHE	51.600	176.86	32.854
P1	1.9000	30.116	0.2060
P2	8.6000	38.824	1.2020
P3	3.3000	66.666	0.7920
P4	27.800	87.280	8.7350
GE	1000.0	39.166	141.00

Table 6.22 Costs of work produced by the biogas engine powered cogeneration according to the SPECO.

	Cost of Work Produced by Biogas Engine	
Component	Unit Exergoeconomic cost c_W($/GJ)	Thermoeconomic cost $\dot{C}_W$($/h)
Gas Engine	39.166	141.00

6.3 Error Analysis

The main measuring devices, calibrated range, accuracy or relative error of various instruments involved in the experiment for various parameters are listed in Table 6.23. All the measuring instruments were calibrated recently before starting the measurements. They were used in the acceptable working condition limits of the instruments and usually operated for more than an hour before starting the reading. Therefore, only occasional errors are considered during the experiment. An error analysis based on the accuracies of the direct measurements is conducted to determine the maximum possible errors of these deduced parameters, such as the fuel exergy, product exergy, unit exergy consumption and unit marginal exergy cost of product of every component. The adopted analysis method is the differential method of propagating errors based on Taylor's theorem. It gives the maximum error Δy of a function $y = f(x_1, x_2, x_3, \ldots x_n)$ as follows,

$$\Delta y = \sqrt{\Sigma \left(\frac{\partial f}{\partial x_i} \Delta x_i \right)^2} \tag{6.1}$$

As a result, the maximum relative root mean square errors of every component during the experiment are tabulated in Table 6.24. It can be seen that the greatest possible error was ±1.854% according to fuel of intercooler. It should be clearly noted that the estimated errors in the measurements of the derived quantities do not significantly influence the final results.

Table 6.23 Specification of the different measuring devices.

Instrument	Parameter	Calibrated range	Accuracy
Platinum resistance temperature sensor	Water inlet and outlet temperature of a unit	0-100	±0.01 ˚C
Platinum resistance temperature sensor	Fuel gas temperature	0-100	±0.10 ˚C
k-type thermocouple	Exhaust gas temperature	0-600	± 1.00 ˚C

Table 6.24 Summary of the estimated relative errors.

Components	Maximum relative errors	
	Fuel $\dot{E}x_F$	Product $\dot{E}x_P$
Compressor	±1.437%	±0.042%
Turbine	±1.261%	±1.437%
Intercooler	±1.854%	±1.427%
EGHE	±1.218%	±0.122%
HE 1	±0.133%	±0.312%
HE 2	±0.934%	±1.724%
LOHE	±0.000%	±0.426%
P1	±0.000%	±0.000%
P2	±0.000%	±0.000%
P3	±0.000%	±0.000%
P4	±0.000%	±0.000%
GE	±0.248%	±0.000%

6.4 Optimization Results

6.4.1 TFA Results

6.4.1.1 Adopted BPCS for TFA

A 12 component biogas powered cogeneration system and detailed information about this system is given in chapter 4. TFA optimization method will be applied on this system with a difference of reducing the units. Biogas engine powered cogeneration is adopted according to TFA principles and last shematic is given in Figure 6.2. State properties of the adopted system is given in Table 6.25.

In fact Figure 6.2 is not adequate to describe the optimization functions which is requested by TFA. A new diagram is formed and it is called as functional diagram, thus Figure 6.3 represented functional diagram of adopted biogas powered cogeneration. Figure 6.3. describes the unit products on exergetic basis. Two kinds of new units are added to the Figure 6.2; one is junction (unit no 13) others are branching points. Responsibilities of a junction and a branching point are explained before.

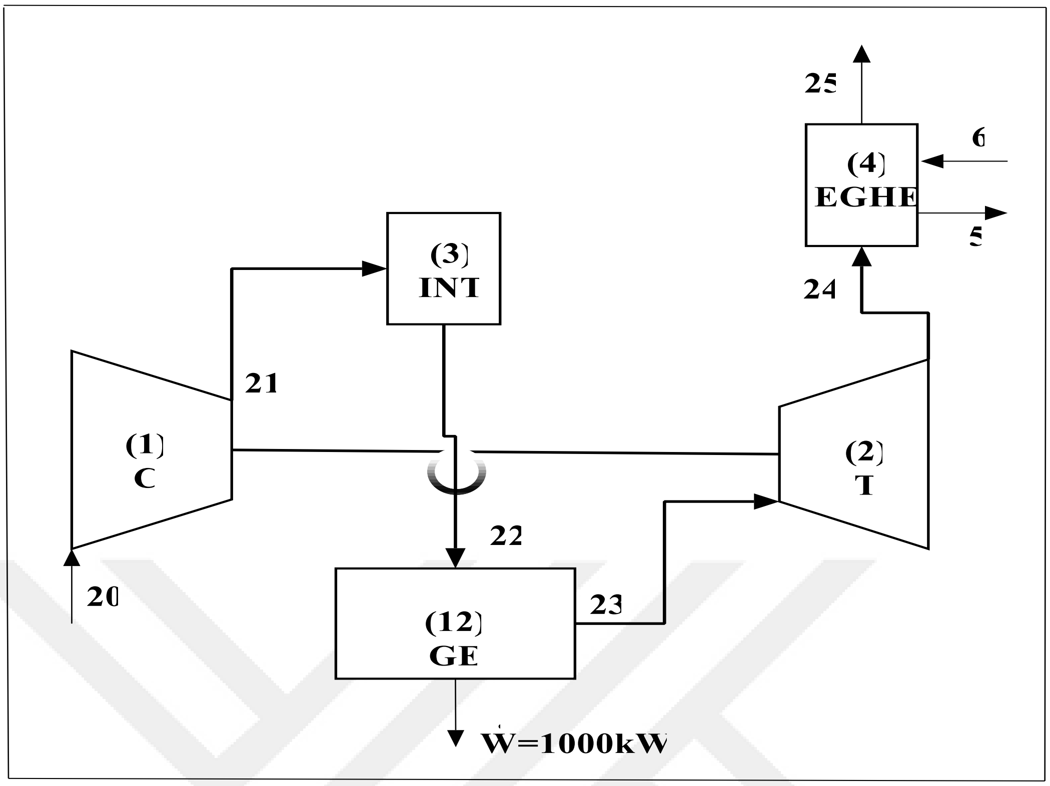


Figure 6.2 Adopted schematic of biogas engine powered cogeneration for TFA.

Table 6.25 State properties of the adopted system.

State No	Fluid	Pressure P (bar)	Temperature T (°C)	Mass flowrate ṁ (kg/sn)	Enthalpy h (kJ/kg)	Entropy s (kJ/kg)	Energy rate, Ė (kW)	Exergy rate, Ėx (kW)
0	Air	1.00	25.00	-	298.6	5.6990	0.0000	0.0000
0’	Water	1.00	25.00	-	104.2	0.3648	0.0000	0.0000
0’’	Biogas	1.00	25.00	-	-4650	11.620	---	---
20	Air-fuel	1.00	25.00	1.500	298.6*	5.6990*	0.0000	4046.40
21	Air-fuel	1.90	116.9	1.500	391.2*	5.7860*	155.21	4154.13
22	Air-fuel	1.90	51.00	1.500	324.7*	5.5990*	43.474	4136.23
23	Exhaust gas	2.40	460.0	1.500	749.4	6.3750	676.20	374.300
24	Exhaust gas	1.17	360.6	1.500	642.9	6.4250	516.50	192.250
25	Exhaust gas	1.00	65.00	1.500	338.8	5.8260	60.340	3.69200
5	Water	6.10	82.80	20.88	347.1	1.1080	5071.7	447.300
6	Water	3.40	88.00	20.88	368.7	1.1690	5522.7	518.700

6.4.1.2 Thermodynamic Model of TFA for BPCS

In our system all state properties; pressures, temperatures, mass flowrates are known since it is stil running and real. For optimization, variables that play important role in the design and operation of the system should be selected. Therefore, r_C, ε_C, ε_T, T_{23} may choosen as variables. r_C is the compressor pressure ratio; ε_C, ε_T are the exergetic efficiencies of compressor and turbine respectively; T_{23} is the turbine inlet temperature for the exhaust gas from the biogas fuelled engine. Other necessary parameters are also determined by arranging thermodynamic equations from Equations (6.18) to (6.27). These equations help to form the cost functions of units.

$$r_C = \frac{P_{21}}{P_{20}} \tag{6.18}$$

$$\varepsilon_C = \frac{y_1}{W_C} \tag{6.19}$$

$$\dot{W}_C = \dot{m}_a\, c_{pa}(T_{21} - T_{20}) \tag{6.20}$$

$$r_T = \frac{P_{23}}{P_{24}} \tag{6.21}$$

$$\varepsilon_T = \frac{y_{1,2} + y_{13,2}}{\dot{W}_T} \tag{6.22}$$

$$\dot{W}_T = \dot{m}_g\, c_{pg}(T_{23} - T_{24}) \tag{6.23}$$

$$A_{INT} = \frac{\dot{m}_a c_{pa}(T_{21} - T_{22})}{U \Delta T_{INT}} \tag{6.24}$$

$$\Delta T_{INT} = \frac{(T_{22} - T_{12}) - (T_{21} - T_{13})}{\ln \frac{(T_{22} - T_{12})}{(T_{21} - T_{13})}} \tag{6.25}$$

$$A_{EGHE} = \frac{\dot{m}_g c_{pg}(T_{21} - T_{22})}{U \Delta T_{EGHE}} \tag{6.26}$$

$$\Delta T_{EGHE} = \frac{(T_{25} - T_5) - (T_{24} - T_6)}{\ln \frac{(T_{25} - T_5)}{(T_{24} - T_6)}} \tag{6.27}$$

ΔT denotes the temperature difference on the both sides of any heat exhanger, A is its heat transfer area, and g is exhaust gas. (Exhaust gas is assumed to show the features of air, c_{pa}= c_{pg}= 1.005 kJ / kg.K).

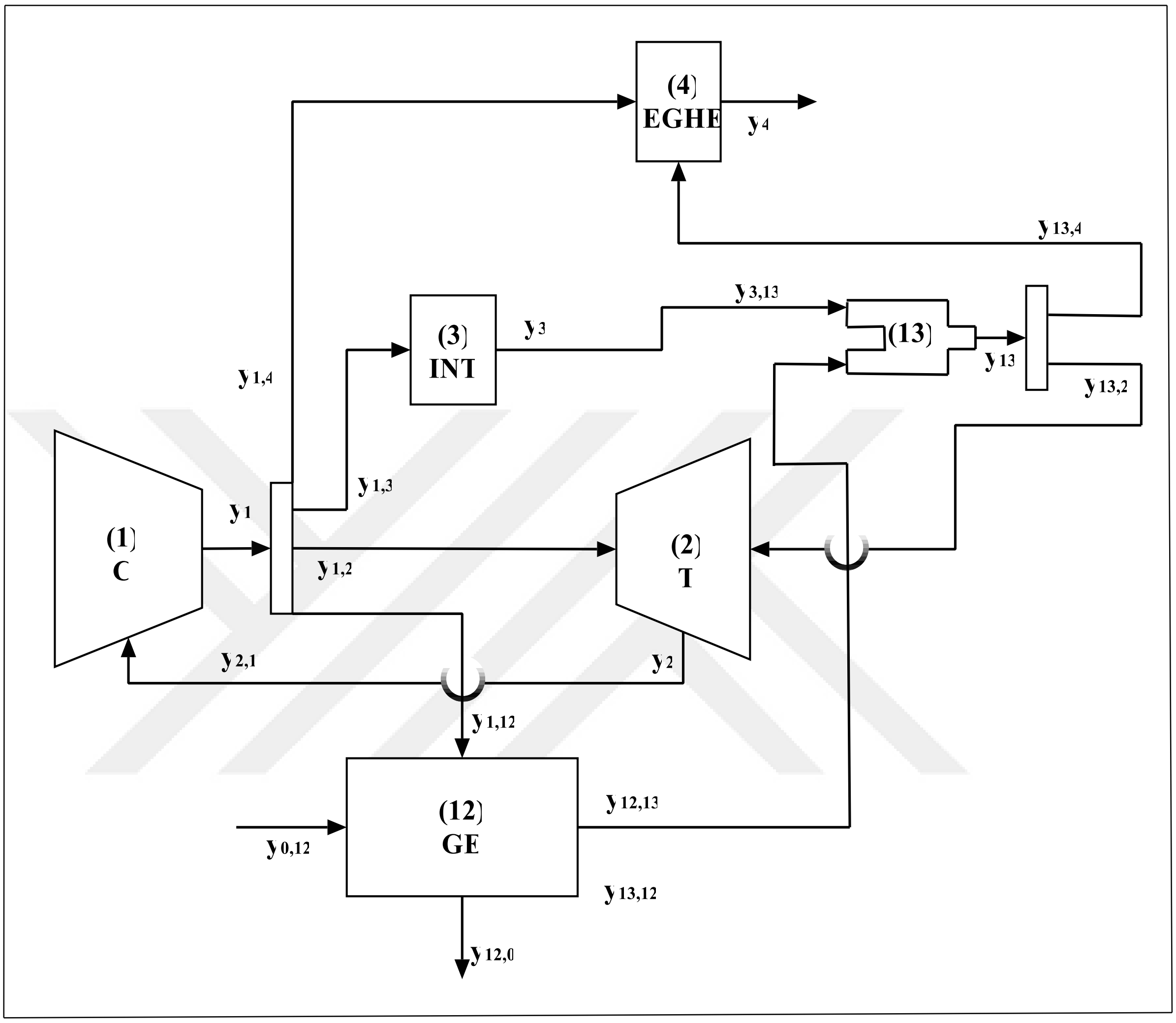


Figure 6.3 Functional diagram of adopted biogas powered cogeneration system.

6.4.1.3 Economic Model of TFA for BPCS

Design characteristics are the most important factors which help to form the capital cost. Therefore decomposed equations are written to calculate installed capital cost of each component. The annuliazed capital cost of each component comprising depreciation and maintanence is demonstrated as,

$$\dot{Z}_i = FCR \cdot \emptyset \cdot Ç_i \quad (6.28)$$

$Ç_i$, installed capital cost function of unit i

FCR , annual fixed charge rate

Ø , maintanence factor.

The total annual cost for the system is written in Equation (6.29),

$$\dot{Z} = \sum_{i=1}^{n} \dot{Z}_i + c_f\, \dot{m}_f\, H_f\, t \tag{6.29}$$

c_f , cost of fuel per unit of energy

H_f, lower heating value of the fuel

t , time period of operation during a year.

Cost functions according to units are performed as,

$$Ç_1 = \frac{c_{11}\dot{m}_a}{c_{12} - \eta_C}\, r_C \ln r_C \tag{6.30}$$

$$Ç_2 = \frac{c_{21}\dot{m}_g}{c_{22} - \eta_T}\, \ln r_T [1 + \exp(c_{23}T_{23} - c_{24})] \tag{6.31}$$

$$Ç_3 = c_{31} A_{Intercooler}^{0.6} \tag{6.32}$$

$$Ç_4 = c_{41} A_{EGHE}^{0.6} \tag{6.33}$$

$$Ç_{12} = \frac{c_{121}\dot{m}_g}{c_{122} - \eta_{GE}}\, \ln r_{GE} [1 + \exp(c_{123}T_{22} - c_{124})] \tag{6.34}$$

Formulations are arranged in the perspective of TFA principles [75,76]. Nominal values of cost parameters are denoted as c_{ij} and represented in Table 6.26.

Table 6.26 Nominal values of cost parameters.

t = 8030 hour /year	c_{12} = 0.9	c_{31} = 525.737 \$/ $m^{1.2}$
c_f = 6.35 \$/GJ	c_{21} = 30745.8 \$/(kg/sn)	c_{41} = 67.015 \$/ $m^{1.2}$
FCR = 0.10 $(year)^{-1}$	c_{22} = 0.92	c_{121} = 72150.3 \$/(kg/sn)
Ø =1.06	c_{23} = 0.036 K^{-1}	c_{122} = 0.9
c_{11} = 5758.91 \$/(kg/sn)	c_{24} = 54.4	c_{123} = 0.018 K^{-1} , c_{124} = 26.4

6.4.1.4 Functional Analysis

Functional analysis of the system in Figure 6.23 starts with the compressor,

1-) Compressor

The function of the compressor is increasing the exergy of air from state 20 to state 21 (although air-fuel mixture is charged to compressor only incresing air exergy is considered because the biogas chemical feature is mostly important parameter to produce work from gas engine. Also its physical exergy is negligible compared to its chemical exergy),

$$y_1 = \dot{m}_a (\dot{e}x_{21air} - \dot{e}x_{20air}) = \dot{m}_a \left[(\dot{e}x^T_{21air} - \dot{e}x^T_{20air}) + R_a T_0 \ln \frac{P_{21}}{P_{20}} \right] \quad (6.35)$$

$$(\dot{e}x^T_{21air} - \dot{e}x^T_{20air}) = c_{pa} \left(T_{21} - T_{20} - T_0 \ln \frac{T_{21}}{T_{20}} \right) \quad (6.36)$$

Compressor uses shaft power which is generated by the turbine (unit 2),

$$y_{2,1} = \dot{W}_C = \dot{m}_a \, c_{pa}(T_{21} - T_{20}) \quad (6.37)$$

The mechanical exergy resulting from pressure difference from the environment is served to all other units according to the pressure drop in each unit,

$$y_{1,2} = \dot{m}_a R_a T_0 \left[\ln \frac{P_{23}}{P_{24}} \right] \quad (6.38)$$

$$y_{1,4} = \dot{m}_a R_a T_0 \left[\ln \frac{P_{24}}{P_{25}} \right] \quad (6.39)$$

$$y_{1,12} = \dot{m}_a R_a T_0 \left[\ln \frac{P_{22}}{P_{23}} \right] \quad (6.40)$$

The thermal exergy resulted from temperature increase in the compressor is given to intercooler,

$$y_{1,3} = \dot{m}_a (\dot{e}x^T_{21air} - \dot{e}x^T_{20air}) \quad (6.41)$$

2-) Turbine

Turbine generates shaft power,

$$y_2 = \dot{W}_T = \dot{m}_g\, c_{pg}(T_{23} - T_{24}) \tag{6.42}$$

$\dot{m}_g$ is the mass of exhaust gases from gas engine and it is denoted as the summation of the masses of biogas and air.

Turbine uses mechanical exergy from compressor $y_{1,2}$, and thermal exergy from junction,

$$y_{13,2} = \dot{m}_g\, (\dot{e}x^T_{23air} - \dot{e}x^T_{24air}) \tag{6.43}$$

<u>3-) Intercooler</u>

The product of the intercooler is given to the junction,

$$y_3 = \dot{m}_a\, (\dot{e}x^T_{21air} - \dot{e}x^T_{22air}) \tag{6.44}$$

<u>4-) EGHE</u>

EGHE is the focus unit for the heat production of this cogeneration system, it gives the excess heat of exhaust gases to the water. Its product is,

$$y_4 = \dot{m}_W\, (\dot{e}x_6 - \dot{e}x_5) \tag{6.45}$$

It uses thermal exergy from junction,

$$y_{13,4} = \dot{m}_a\, (\dot{e}x^T_{24air} - \dot{e}x^T_{25air}) \tag{6.46}$$

<u>12-) GE</u>

Product of gas engine is, $\dot{W}$

$$y_{12,0} = 1000 \text{ kW} \tag{6.47}$$

By consuming fuel

$$y_{0,12} = \dot{m}_f\, H_f \tag{6.48}$$

Air fuel mixture is charged to the compressor at the beginning of the process but its chemical energy is used in the gas engine. In Equation (6.48) energy of fuel is used instead of exergy. This choice is not incorrect, provided that cost of fuel per unit of energy is used. After producing work gas engine increases the exergy of exhaust gases and gives this exergy to the junction,

$$y_{12,13} = \dot{m}_g\, \dot{e}x_{23} - \dot{m}_a\, \dot{e}x_{22} \tag{6.49}$$

6.4.1.5 Statement of The Optimization Problem

Minimization of the total cost rate of the system is selected as the optimization objective function,

$$\min_{x} \dot{Z} = \sum_{i=1}^{12} \dot{Z}_i + c_f\, \dot{m}_f\, H_f \tag{6.50}$$

where $x = (r_C,\ \varepsilon_C,\ \varepsilon_T,\ T_{23})$,

Any other independent set of variables could be selected from the above arguments. The one selected here facilitates the calculations performed with the system of Equations from (6.18) to (6.27).

In addition to the equality constraints given between the equations fom (6.41) to (6.49) the following inequality constraints are embarked.

$$T_{21}\text{-}T_{22} \geq 0\,,\quad T_{23}\text{-}T_{22} \geq 0\,,\quad T_{23}\text{-}T_{24} \geq 0\,,\quad T_{24}\text{-}T_{25} \geq 0\,,\quad T_6\text{-}T_5 \geq 0 \tag{6.51}$$

The necessary cost functions to be used in calculations for each unit are arranged as,

$$C_1 = Z_1 + \lambda_2 y_{2,1} \tag{6.52}$$

$$C_2 = Z_2 + \lambda_1 y_{1,2} + \lambda_{13} y_{13,2} \tag{6.53}$$

$$C_3 = Z_3 + \lambda_1 y_{1,3} \tag{6.54}$$

$$C_4 = Z_4 + \lambda_{1,4} y_{1,4} + \lambda_{13,4} y_{13,4} \tag{6.55}$$

$$C_{12} = Z_{12} + \lambda_1 y_{1,12} + \lambda_{0,12} y_{0,12} \tag{6.56}$$

$$C_{13} = \lambda_3 y_{3,13} + \lambda_{12} y_{12,13} \tag{6.57}$$

After the application of TFA to the system, Table 6.27 indicates the optimum results for the desicion variables. Calculated optimum exergetic flows are performed in

Table 6.27 Optimization results for nominal set of adopted BPCS parameter values according to TFA.

Variable	TFA
r_C	1.9
ε_C	0.72
ε_T	0.89
T_{23}	460˚C

Table 6.28 Calculated function values according to TFA at the optimum point.

Functions	$\dot{E}x$ (kW)
y_1	91.5700
$y_{1,2}$	84.1890
$y_{1,3}$	16.5670
$y_{1,4}$	18.4090
$y_{1,12}$	-27.437
y_2	151.503
$y_{2,1}$	126.500
y_3	15.2340
y_4	71.4000
y_{12}	1000.00
$y_{12,13}$	297.579
$y_{0,12}$	2308.06
y_{13}	263.289
$y_{13,2}$	84.7210
$y_{13,4}$	163.334

Table 6.29 Calculated Lagrange multipliers and unit exergoeconomic costs for adopted BPCS according to TFA.

Lagrange Multiplier λ ($/GJ)	Unit Exergoeconomic Cost, c ($/GJ)
λ_1= 16.91	c_1= 17.70
λ_2= 12.63	c_2= 12.90
λ_3= 19.38	c_3= 20.00
λ_4= 15.53	c_4= 15.53
λ_{12}= 0.04	c_{12}= 26.86
λ_{13}= 4.70	c_{13}= 4.700

Table 6.28 and Lagrange multipliers also unit exergoeconomic costs for the system are shown in Table 6.29.

Thermodynamic optimization modelling of the adopted system is performed at Table 6.27. Table 6.28 is arranged depending on the products of the units distributed to other units. The optimum cost values are calculated with the help of the Lagrange multipliers of TFA method and shown in Table 6.29. Lagrange multiplier values are generally compatible with the unit cost values. This is expected in terms of the accuracy of the calculations. However, the values of c_{12} and λ_{12} are very different from each other, this can be explained as the cost of fuel added to the gas engine.

The product cost of EGHE is very high in the cost analysis methods which are implemented on this system. However, it is observed that this cost decreased considerably as a result of optimization. All units are taken into account in cost accounting analysis methods and calculations are done in this context. TFA optimization is concentrated only on the gas line, so the effect of the other units of the system is ignored. The cost reduction of the EGHE product can be explained by this way.

When we look at the optimized costs of the products of other units, it is clear that the values have declined considerably. Compared to ECT, the most comprehensive cost analysis, TFA's compressor and turbine optimized product costs have reduced by almost half. Unfortunately, especially on the collection of attention, gas engine product cost does not decrease much. Since ECT gives 29.783 $/GJ as exergoeconomic cost for produced work, wheras TFA gives 26.86 $/GJ.

Gas engine used in our cogeneration system is an internal combustion engine and operates on a four stroke Otto cycle. An ideal Otto cycle analysis is performed for the biogas powered engine in our system by using the following relationships based on the processes shown in Figure 6.4 [109].

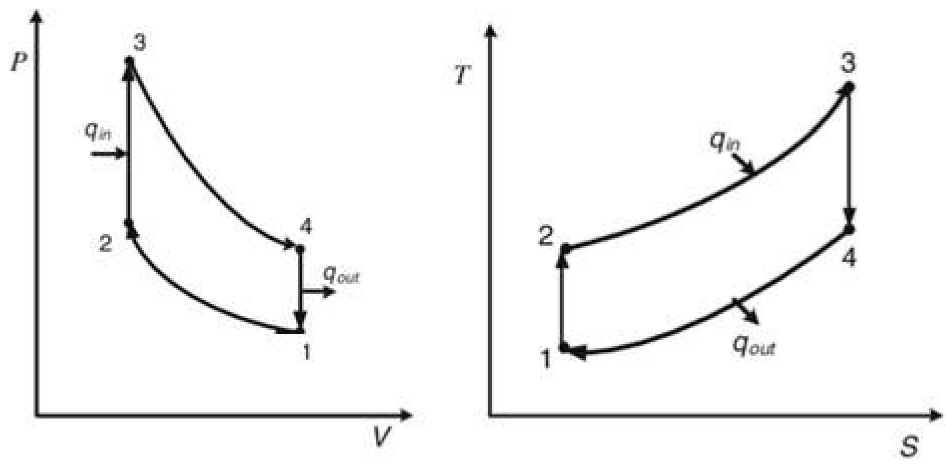


Figure 6.4 P-V and T-S diagrams of ideal Otto cycle.

Process 1-2 ; isentropic compression stroke

$T_2=T_1(V_1/V_1)^{k-1} = T_1(r_C)^{k-1}$, $P_2= P_1(V_1/V_1)^k=P_1(r_C)^k$, $q_{1-2} = 0$

Process 2-3 ; constant-volume heat input (combustion)

$w_{2-3} = 0$, $q_{in}= c_v(T_3 - T_2)$, $T_3= T_{max}$, $P_3 = P_{max}$

Process 3-4 ; isentropic power or expansion stroke

$q_{3-4}= 0$, $T_4=T_3(V_3/V_4)^{k-1} = T_3(1/r_C)^{k-1}$, $P_4= P_3(V_3/V_4)^k = P_3(1/r_C)^{k-1}$, $w_{in}= c_v(T_3 - T_4)$

Process 4-1 ; constant-volume heat rejection (exhaust blowdown)

$w_{4-1}= 0$, $q_{out}= c_v(T_5 - T_4)$

The input data for biogas engine engines powered cogeneration plant and average air properties as;

$T_1= 324$ K , $P_1=190$ kPa , $r_C=13.4$, k= 0.4 , $c_V = 0.718$ KJ/kgK

Using above process equations results of ideal Otto cycle analysis are obtained as;
$T_2= 917$ K , $P_2=7264.753$ kPa , $T_4= 9122.113$ K , $P_4= 2854.025$ kPa , $q_{in}=17892$ kJ/kg , $q_{out}= 6317.045$ kJ/kg , $\dot{W}_{net}=1493.17$ kW

The value for the net work of gas engine is found as 1493.17 kW. In this perspective, optimization process is applied on the range of 1000 kW and 1493.17. Figure 6.7 presents how exergetic efficiency changes between this range.

Optimization graphs of TFA are stated as below.

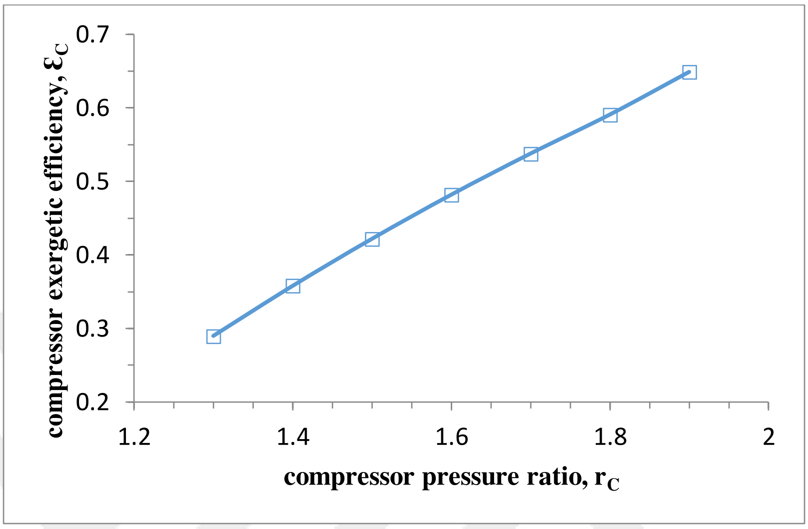


Figure 6.5 Compression pressure ratio versus exergetic efficieny.

Figure 6.5 and 6.6 represent the affect of compression pressure ratio on the exergetic efficiency of compressor also its unit exergoeconomic cost. Optimized value for compressure pressure ratio is determined as 1.9 as seen in Table 6.26, for its smaller values exergetic efficiency decreases. Otherwise cost for this unit increases.

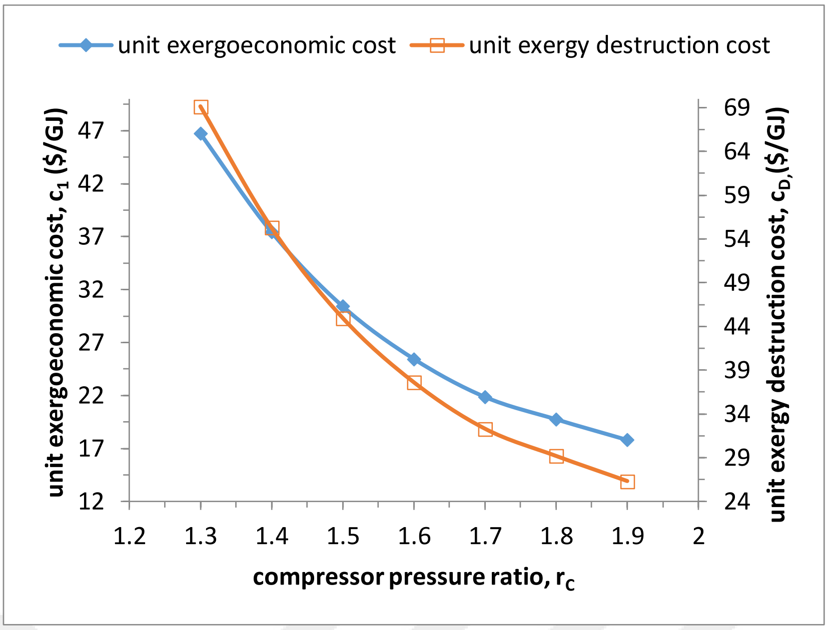


Figure 6.6 Variation of compressor product cost and exergy destruction cost rates with respect to the pressure ratio of compressor.

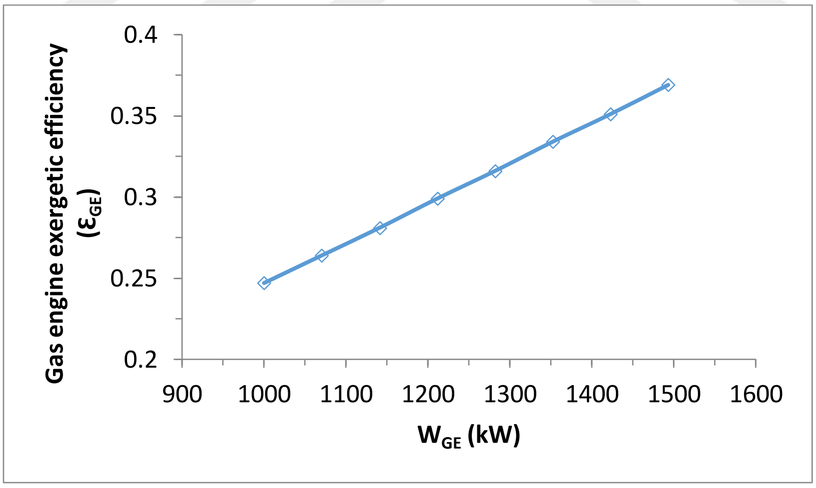


Figure 6.7 Gas engine work, W_{GE} versus exergetic efficiency.

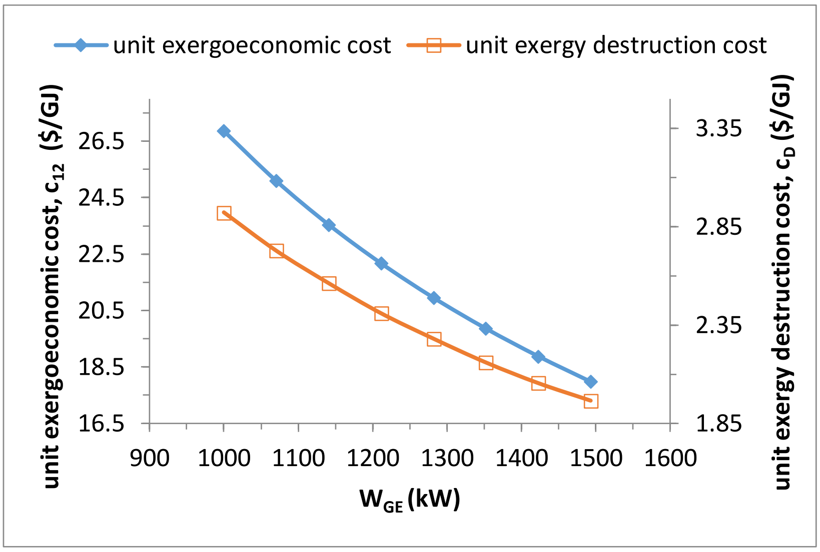


Figure 6.8 Variation of gas engine product cost and exergy destruction cost rates with respect to gas engine work, W_{GE}.

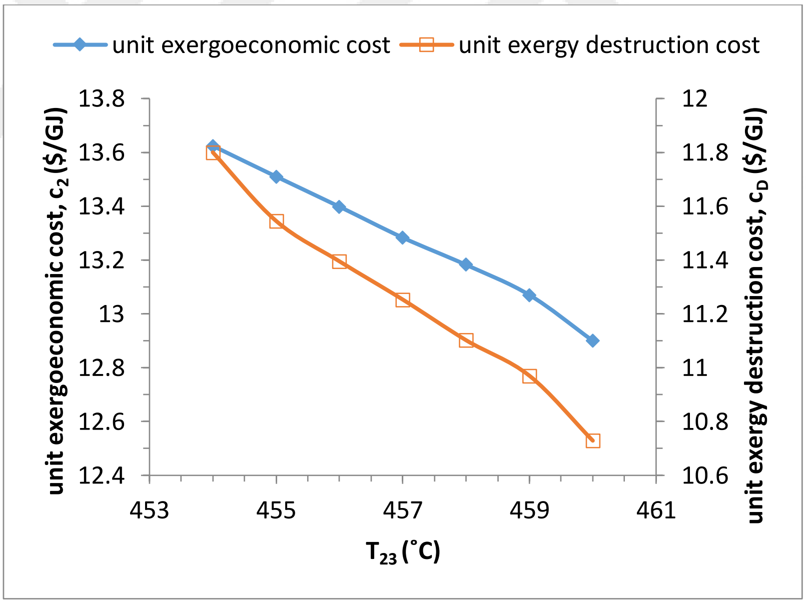


Figure 6.9 Variation of turbine product cost c_2 and exergy destruction cost rates with respect to the turbine inlet temperature T_{23}.

6.4.2 EFA Results

6.4.2.1 Functional Diagram of EFA for Adopted BPCS

EFA underlines the unit function which is explained as the only major product, and it can or can not have a direct relation with one of the physical units in the system. For example, gas engine’s primary product is the work secondary product is exhaust gas which handled by a branch, see Figure 6.10. Branch referred to a splitter and physically splits a stream does not have a physical counterpart. Another branch is used in the case of intercooler, for delivering a resource, such as mechanical exergy to a unit in order to prevent the losses resulted from pressure drop.

Regarding with junctions, they can be called as a mixer which physically mix two streams together, the situation is represented in Figure 6.11. It also does not have physical counterpart. A junction purposes to join the major product of a unit with the rest of the system. Conceptually, branches and junctions tend to define a unit’s function. However, a point must be keep in view that gas engine’s primary product does not take part in the exergy loop since it is delivered to a generator to obtain electricity.

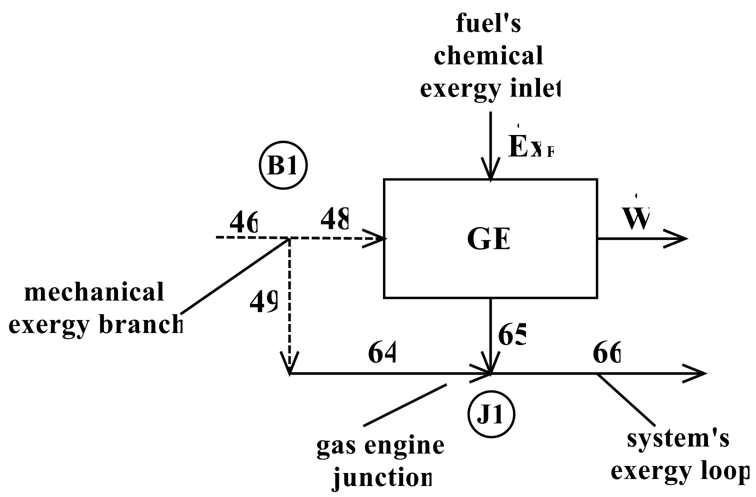


Figure 6.10 Gas engine branch and junction schematic diagram.

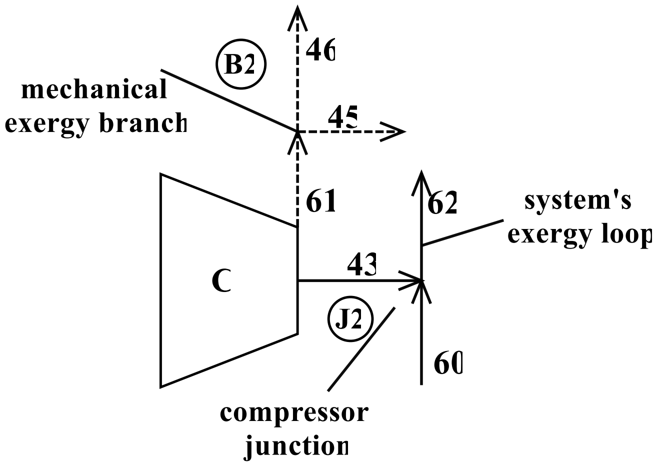


Figure 6.11 Compressor branch and junction schematic diagram.

All the unit functions are remarked along the exergy (chemical, mechanical, thermal or negentropy) they used as fuel and local structures such as Figure 6.10 and Figure 6.11, finally the overall thermoeconomic structure can be arranged for the system. EFA demonstrates this structure as a functional diagram which appears for adopted BPCS in Figure 6.12.

When defining exergetic lines, numbers are used, on the other hand y values represent the corresponding unit's product, using this notation is attributed to TFA. There are four kinds of loops are choosen in Figure 6.12. These are power loop, system's exergy loop, negentropy loop, mechanical exergy loop, which complete the thermoeconomic structure of the system. EGHE has been chosen to have the dual functions of heating the water coming from the other part and utilising the excess heat of exhaust gases. Other units strived for removing of the entropy which they produce and accumulate and this struggle is quantified in terms of negentropy. This additional function is included to study of effect on the internal economy of the system.

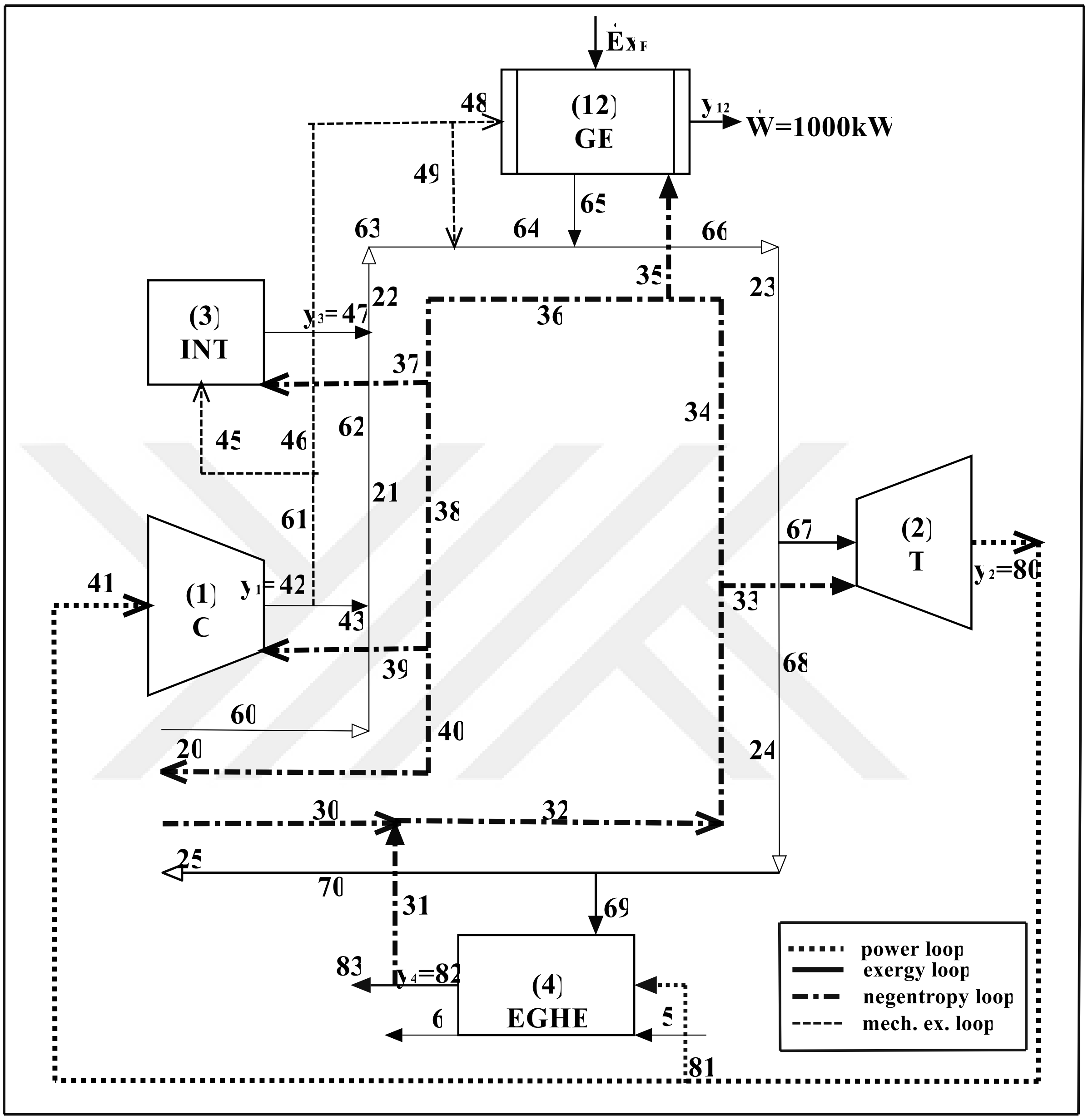


Figure 6.12 Functional diagram for adopted BPCS according to EFA.

The unit functions and corresponding fuels are described as follows,

<u>1-) Compressor</u>

Function; to increase the pressure of air-fuel mixture

Fuel; mechanical exergy

2-) Turbine

Function; to distribute the work for internal use

Fuel; work

3-) Intercooler

Function; to cool the air-fuel mixture

Fuel; negentropy (negentropy can be called as negative entropy, refers to the degree of order or organization within a system).

4-) EGHE

Function; to heat the water coming from the other part of the system

Fuel; system's exergy

12-) GE

Function; to deliver work for external use

Fuel; chemical exergy

In the next section thermoeconomic model of EFA for the system will be mentioned.

6.4.2.2 Thermoeconomic Model of EFA for BPCS

Thermoeconomic structure for EFA is signified in chapter 5. To obtain the results the mathematical equivalent must be developed. General mathematical functions for optimization problem appearing in Equation (5.45) - (5.53) are derived to express the desicion variables of each unit or system product function. These derivations of each unit also associated junctions and branches are given below.

1- Compressor

$$\dot{Z}_1 = \frac{FCR\ .\ \emptyset}{(N)(3600)} \frac{c_{11}\dot{m}_a}{c_{12}-\eta_C} r_C \ln r_C \frac{\xi_1}{\eta_{II_C}} \dot{E}x_{42} \tag{6.58}$$

$$\dot{E}x_{41} = \left(\frac{1}{\eta_{II_C}}\right)\dot{E}x_{42} \tag{6.59}$$

$$\dot{E}x_{39}^{n} = \left(\frac{1-\eta_{II_C}}{\eta_{II_C}}\right)\dot{E}x_{42} \quad (6.60)$$

$$\xi_1 = \frac{1}{c_{pa}\,(T_{21} - T_{20}) / \eta_{M_C}} \quad (6.61)$$

$$\eta_{II_C} = \frac{c_{pa}\left(T_{21}\text{-}T_{20}\text{-}\ T_0 \ln\frac{T_{21}}{T_{20}}\right) + \left(R_a T_0 \ln\frac{P_{21}}{P_{20}}\right)}{c_{pa}\,(T_{21} - T_{20}) / \eta_{M_C}} \quad (6.62)$$

Compressor branches and junctions

$$\dot{E}x_{43} = \dot{m}_a c_{pa}\left(T_{21}\text{-}T_{20}\text{-}\ T_0 \ln\frac{T_{21}}{T_{20}}\right) \quad (6.63)$$

$$\dot{E}x_{60} = \dot{m}_a\left[c_{pa}\left(T_{20}\text{-}T_0\text{-}\ T_0 \ln\frac{T_{20}}{T_{20}}\right) + \left(R_a T_0 \ln\frac{P_{20}}{P_{20}}\right)\right] = 0 \quad (6.64)$$

$\dot{E}x_{62} = \dot{E}x_{43} + \dot{E}x_{60}$ (junction) (6.65)

$\dot{E}x_{42} = \dot{E}x_{61} + \dot{E}x_{43}$ (branch) (6.66)

$\dot{E}x_{40}^{n} = \dot{E}x_{38}^{n} - \dot{E}x_{39}^{n}$ (branch) (6.67)

2- Turbine

$$\dot{Z}_2 = \frac{FCR\ .\ \emptyset}{(N)(3600)}\ \frac{c_{21}}{c_{22} - \eta_T}\ \ln r_T\ \frac{[1 + \exp\,(c_{23}T_{23} - c_{24})]}{\eta_{M_T}(h_{23} - h_{24})}\ \dot{E}x_{80} \quad (6.68)$$

$$\dot{E}x_{67} = \left(\frac{1}{\eta_{II_T}}\right)\dot{E}x_{80} \quad (6.69)$$

$$\dot{E}x_{33}^{n} = \left(\frac{1-\eta_{II_T}}{\eta_{II_T}}\right)\dot{E}x_{80} \quad (6.70)$$

$$\eta_{II_T} = \frac{\eta_{M_T}(h_{23} - h_{24})}{(h_{23} - h_{24}) - T_0\,(s_{23} - s_{24})} \quad (6.71)$$

Turbine branches and junctions

$\dot{E}x_{68} = \dot{E}x_{66} + \dot{E}x_{67}$ (branch) (6.72)

$\dot{E}x_{80} = \dot{E}x_{81} + \dot{E}x_{41}$ (branch) (6.73)

$$\dot{E}x^{n}_{34} = \dot{E}x^{n}_{32} - \dot{E}x^{n}_{33} \qquad \text{(branch)} \qquad (6.74)$$

3- Intercooler

$$\dot{Z}_3 = \frac{FCR\ .\ \emptyset}{(N)(3600)}\ c_{31} \left(\frac{\xi_{31}}{U\Delta T}\right)^{0.6} \left(\dot{E}x_{47}\right)^{0.6} \qquad (6.75)$$

$$\dot{E}x_{45} = \left(\frac{1}{\xi_{32}}\right) \dot{E}x_{47} \qquad (6.76)$$

$$\dot{E}x^{n}_{37} = \left(\frac{1}{\xi_{33}}\right) \dot{E}x_{47} \qquad (6.77)$$

$$\xi_{31} = \frac{(h_{22} - h_{21})}{(h_{22} - h_{21}) - c_{pa}\ T_0\ \ln\frac{T_{21}}{T_{22}}} \qquad (6.78)$$

$$\xi_{32} = \frac{(h_{22} - h_{21}) - c_{pa}\ T_0\ \ln\frac{T_{21}}{T_{22}}}{R_a T_0 \ln\frac{P_{21}}{P_{22}}} \qquad (6.79)$$

$$\xi_{33} = \frac{(h_{22} - h_{21}) - c_{pa}\ T_0\ \ln\frac{T_{21}}{T_{22}}}{T_0(s_{22} - s_{21})} \qquad (6.80)$$

Intercooler branches and junctions

$$\dot{E}x_{47} = \dot{m}_a c_{pa} \left(T_{21} - T_{22} - T_0 \ln\frac{T_{21}}{T_{22}}\right) \qquad (6.81)$$

$$\dot{E}x_{46} = \dot{E}x_{61} + \dot{E}x_{45} \qquad \text{(branch)} \qquad (6.82)$$

$$\dot{E}x_{63} = \dot{E}x_{47} + \dot{E}x_{43} \qquad \text{(junction)} \qquad (6.83)$$

$$\dot{E}x^{n}_{38} = \dot{E}x^{n}_{36} - \dot{E}x^{n}_{37} \qquad \text{(branch)} \qquad (6.84)$$

4- EGHE

$$\dot{Z}_4 = \frac{FCR\ .\ \emptyset}{(N)(3600)}\ c_{41} \left(\frac{\xi_{41}}{U\Delta T}\right)^{0.6} \left(\dot{E}x_{82}\right)^{0.6} \qquad (6.85)$$

$$\dot{E}x_{81} = \left(\frac{1}{\xi_{42}}\right) \dot{E}x_{82} \qquad (6.86)$$

$$\dot{E}x_{69}^{n} = \left(\frac{1-\xi_{43}}{1-\xi_{44}}\right)\dot{E}x_{82} \quad (6.87)$$

$$\xi_{41} = \frac{(h_{24}-h_{25})}{(h_{24}-h_{25}) - c_{pa}\, T_0 \ln\frac{T_{24}}{T_{25}}} \quad (6.88)$$

$$\xi_{42} = \frac{(h_6-h_5) - c_{pa}\, T_0 \ln\frac{T_6}{T_5}}{R_a T_0 \ln\frac{P_5}{P_6}} \quad (6.89)$$

$$\xi_{43} = \frac{T_0\,(s_{24}-s_{25})}{(h_{24}-h_{25})} \quad (6.90)$$

$$\xi_{44} = \frac{c_{pa}\, T_0 \ln\frac{T_6}{T_5}}{(h_6-h_5)} \quad (6.91)$$

EGHE branches and junctions

$$\dot{E}x_{82} = \dot{m}_w[(h_6-h_5) - T_0(s_{24}-s_{25})] \quad (6.92)$$

$$\dot{E}x_{31}^{n} = \dot{m}_g T_0\,(s_{24}-s_{25}) \quad (6.93)$$

$$\dot{E}x_{70} = \dot{E}x_{68} - \dot{E}x_{69} \qquad \text{(branch)} \quad (6.94)$$

$$\dot{E}x_{82} = \dot{E}x_{83} - \dot{E}x_{31} \qquad \text{(branch)} \quad (6.95)$$

$$\dot{E}x_{32}^{n} = \dot{E}x_{31}^{n} + \dot{E}x_{30}^{n} \qquad \text{(junction)} \quad (6.96)$$

12- GE

$$\dot{Z}_{12} = \frac{FCR\,.\,\emptyset}{(N)(3600)}\,\frac{c_{121}\dot{m}_g}{c_{122}-\eta_{GE}}\,\ln r_{GE}\,\frac{[1+\exp(c_{123}T_{23}-c_{124})]}{\eta_{M_{GE}}(h_{22}-h_{23})}\,\dot{W} \quad (6.97)$$

$$\dot{W} = 1000\text{ kW} \quad (6.98)$$

$$\dot{E}x_{65} = \dot{m}_g\left[c_{pg}\left(T_{23}-T_0-T_0\ln\frac{T_{23}}{T_{20}}\right) + \left(R_a T_0 \ln\frac{P_{23}}{P_0}\right)\right] \quad (6.99)$$

GE branches and junctions

$$\dot{E}x_{49} = \dot{E}x_{46} - \dot{E}x_{48} \qquad \text{(branch)} \quad (6.100)$$

$\dot{E}x_{64} = \dot{E}x_{49} + \dot{E}x_{63}$ (junction) (6.101)

$\dot{E}x_{66} = \dot{E}x_{64} + \dot{E}x_{65}$ (junction) (6.102)

$\dot{E}x^{n}_{36} = \dot{E}x^{n}_{34} - \dot{E}x^{n}_{35}$ (branch) (6.103)

All these equations describe the objective function and all equality constraints. After clarifying the decision variables the thermoeconomic model will be completed. The decision variables are again,

$$x = (r_C,\ \varepsilon_C,\ \varepsilon_T, T_{23}) \quad (6.104)$$

Furthermore physical limits, inequality constraints, on the system should be constituted to complete the thermoeconomic model,

$$T_{23}\text{-}T_{22} \geq 0\ ,\quad T_{22} \leq 51,\quad T_{24}\text{-}T_{25} \geq 295.6 \quad (6.105)$$

6.4.2.3 Internal Economy of EFA for BPCS

The internal economy of the system is determined with the help of the thermoeconomic structure appeared in Figure 6.11. EFA prefers Lagrange multipliers thus the real unit or mariginal costs associated with this thermoeconomic structure and model can be obtained. Objective function and equality constraints constructed with Lagrangian are explained by Equation (5.142)

Each λ appeared in Equation (5.142) represent a unit or mariginal cost corresponding to each unit and they are the undefined multipliers for Lagrange method. Equations (6.58) through (6.103) are connected with the Lagrangian above the costs of unit functions, system product, branches and junctios can be determined.

<u>Unit function costs</u>

$$\dot{C}_1 = \dot{Z}_1 + \lambda_{41}\dot{E}x_{41} + \lambda^{n}_{39}\dot{E}x^{n}_{39} - \lambda_{42}\dot{E}x_{42} \quad (6.106)$$

$$\dot{C}_2 = \dot{Z}_2 + \lambda_{67}\dot{E}x_{67} + \lambda^{n}_{33}\dot{E}x^{n}_{33} - \lambda_{80}\dot{E}x_{80} \quad (6.107)$$

$$\dot{C}_3 = \dot{Z}_3 + \lambda_{45}\dot{E}x_{45} + \lambda^{n}_{37}\dot{E}x^{n}_{37} - \lambda_{47}\dot{E}x_{47} \quad (6.108)$$

$$\dot{C}_4 = \dot{Z}_4 + \lambda_{81}\dot{E}x_{81} + \lambda_{69}\dot{E}x_{69} - \lambda_{82}\dot{E}x_{82} \quad (6.109)$$

$$\dot{C}_{12} = \dot{Z}_{12} + \lambda_{48}\dot{E}x_{48} + \lambda^{n}_{35}\dot{E}x^{n}_{35} - \lambda_{65}\dot{E}x_{65} - \lambda_W\dot{W} \quad (6.110)$$

Branch costs

(Compressor) $\dot{C}_{42} = \dot{C}_{61} + \dot{C}_{43}$, $\dot{C}^{n}_{40} = \dot{C}^{n}_{38} - \dot{C}^{n}_{39}$ (6.111)

(Turbine) $\dot{C}_{68} = \dot{C}_{66} + \dot{C}_{67}$, $\dot{C}_{80} = \dot{C}_{81} + \dot{C}_{41}$, $\dot{C}^{n}_{34} = \dot{C}^{n}_{32} - \dot{C}^{n}_{33}$ (6.112)

(Intercooler) $\dot{C}_{46} = \dot{C}_{61} + \dot{C}_{45}$, $\dot{C}^{n}_{38} = \dot{C}^{n}_{36} - \dot{C}^{n}_{37}$ (6.113)

(EGHE) $\dot{C}_{70} = \dot{C}_{68} - \dot{C}_{69}$, $\dot{C}_{82} = \dot{C}_{83} - \dot{C}_{31}$ (6.114)

(GE) $\dot{C}_{49} = \dot{C}_{46} - \dot{C}_{48}$, $\dot{C}^{n}_{36} = \dot{C}^{n}_{34} - \dot{C}^{n}_{35}$ (6.115)

Junction costs

(Compressor) $\dot{C}_{62} = \dot{C}_{43} + \dot{C}_{60}$ (6.116)

(Intercooler) $\dot{C}^{n}_{38} = \dot{C}^{n}_{36} - \dot{C}^{n}_{37}$ (6.117)

(EGHE) $\dot{C}^{n}_{32} = \dot{C}^{n}_{31} + \dot{C}^{n}_{30}$, $\dot{C}^{n}_{32} = \dot{C}^{n}_{31} + \dot{C}^{n}_{30}$ (6.118)

(GE) $\dot{C}_{64} = \dot{C}_{49} + \dot{C}_{63}$, $\dot{C}_{66} = \dot{C}_{64} + \dot{C}_{65}$ (6.119)

System product costs

$\dot{C}_{W} = \lambda_{W}\dot{W}$ $\dot{C}_{Q} = \lambda_{82}\,\dot{E}x_{82}$ (6.120)

Above cost equations can be derived with the help of the functional diagram of EFA for the system. It is obvious from the Equations (6.106) to (6.110) cost of each unit product is the summation of its capital cost plus its resource cost. Cost of a branch is the addition of its two output cost, however junction cost is equal to the its single output cost. System product costs are identified by the products unit or mariginal cost times its corresponding commodity value.

The optimization of the constrained problem expressed by the Equations (5.45) through (6.120) is converted to unconstrained one owing to Lagrangian method. Actually, system's total cost, Equation (5.45), have to coincide the minimum value of the Lagrangian, Equation (5.142). System's total cost is minimized subjected to its constraints and following results are obtained.

Because the system works on optimum parameters given in Table 5.1, expected results for selected desicion variables are stated in table 6.30.

Table 6.30 Optimization results for decision varibles of adopted system according to EFA.

Variable	EFA
r_C	1.9
ε_C	0.72
ε_T	0.89
T_{23}	460˚C

The primary unit costs for the internal economy of the system are presented in Table 6.31.

Finally, Table 6.32 represents the remaining unit costs at the optimum point for Lagrangian approach.

Table 6.31 The primary unit costs at the optimum point for adopted system according to EFA.

Lagrange Multiplier λ ($/GJ)	EFA
λ_{42}	20.124
λ_{80}	11.984
λ_{47}	21.000
λ_{82}	13.766
λ_W	24.403
λ_{31}^{n}	13.766

6.5 Discussions and Comparision of Cost Accounting Results

Our cost analysis started with a comprehensive and detailed method, ECT. We particularly started to the analysis with this method because the exergetic and thermoeconomic definitions required in all methodologies are described in detail. There are auxiliary equations created based on rules. Owing to these equations, we proceed with sure steps to reach the costs. Firstly exergetic costs for the flows through the system are calculated and indicated in Table 6.4. Unit exergetic cost, κ^*, gives actually true hints about the consumed exergy for achieving a flow. We evaluate the exhaust gas line, flows of 23-24-25, having unit exergetic cost 1. Since there is no extra exergy is consumed to obtain them. Also flow 20 has the same exergetic cost with its exergy, accordance with ECT external fuel rule. However the situation of unit exergetic costs for pumps in Table 6.4 is our initiative, we thought that works given to the pumps are their external fuel and significant results from theorem indicate we are right about these initiatives. Same situation is not valid for compressor fuel which is the work produced by turbine since there is a certain exergetic expense to obtain it.

Table 6.32 Calculated Lagrange multipliers for adopted system according to EFA.

Lagrange Multiplier λ ($/GJ)	EFA
λ_{41}	11.984
λ_{43}	20.124
λ_{45}	0.0000
λ_{46}	20.124
λ_{48}	20.124
λ_{49}	20.124
λ_{60}	0.0000
λ_{61}	20.164
λ_{62}	20.124
λ_{63}	20.545
λ_{65}	9.0810
λ_{64}	20.531
λ_{66}	2.8370
λ_{67}	2.8370
λ_{68}	2.8370
λ_{69}	2.8370
λ_{80}	11.984
λ_{82}	13.760
λ_{83}	13.760
λ^{n}_{32}	7.0000
λ^{n}_{33}	7.0000
λ^{n}_{34}	7.0000
λ^{n}_{35}	7.0000
λ^{n}_{36}	7.0000
λ^{n}_{37}	7.0000
λ^{n}_{38}	7.0000
λ^{n}_{39}	7.0000
λ^{n}_{40}	7.0000

Unit exergoeconomic costs for ECT are determined from the thermodynamics and economic relationship. Equations in the cost hexagon in Figure 6.1 clearly reveal this relationship thus unit exergoeconomic costs of flows obtained as a result of solving these equations are shown in Table 6.6. Finally, fuel and product thermoeconomic costs for all componets according to ECT are shown in Table 6.7 and Table 6.8 respectively. ECT results in a thermoeconomic cost for the gas engine work of

110.065 $/h shown in Table 6.12. A comparison of the values obtained from each method is given in Figure 6.12.

MOPSA theory examines the exergy in two parts; mechanical and thermal. Mechanical exergy deals with pressure while thermal exergy deals with temperature. This procedure needs comprehensive calculations. Table 6.10 shows thermal and mechanical exergy flows, and entropy production rates, at various state points in the system. The general cost balance equation shown in Equation 4.29 is applied to each subsystem to appoint a new unit exergoeconomic cost according to the subsystem's principal product. To achieve this result, detailed equations are performed for gas and water streams. The calculations emphasize that the cost structure of the system is mostly influenced by the entropy production of each component. MOPSA may be the method that shows this fact most obviously, due to the table calculations performed. By the end of the process, the measured exergoeconomic cost production rate of the work from the biogas engine was 85.536 $/h, which is smaller than the result found from ECT. The turbine work is the fuel for the compressor in the ECT principles, which ignore the exergy destruction from turbine to compressor. ECT determines unit exergoeconomic costs for all flows; however, MOPSA defines only two unit exergoeconomic costs, one for gas streams and the other for water streams. Also, the unit exergetic cost for MOPSA is eclipsed by other methods. Therefore the calculated results show differences.

Wonergy is the combination of the energy and exergy flows in a power plant. Since it deems necessary to write energy and exergy balances from Equation (4.30) to Equation (4.33). Then it combines them wonergetically as Equation (4.34) and (4.35). The interesting attemp of this theory is the division of components into three parts; components related to work-only, components related heat-only and common components related with both heat and work. We decided that work-only components are the compressor, turbine, gas engine, EGHE, LOHE, and heat-only component is the HE2 and common components are HE1, P1, P2, P3 and P4. Maybe selecting EGHE and LOHE is confusing for work-only components, however exergetic balance for wonergy given in Table 6.15 justifies our selection. Since LOHE is an important component for the efficient operation of the engine and actually our cogeneration system is a part of a wastewater treatment plant which produce our fuel, biogas, and heated water from EGHE is used for biogas production.The classification of components causes to make easier wonergetic calculations. Eventually Table 6.16 shows the unit exergoeconomic cost and thermoeconomic cost for work-only components as 20.138 $/GJ, 64.419 $/h respectively. Of course, 20.138 $/GJ is multiplied with 1000 kW to reach the true result for the thermoeconomic cost of gas engine work and obtained value is 72.5 $/h. Table 6.16 also shows the unit exergoeconomic result, 202.542 $/GJ for heat-only component which is quite bigger than work-only, yet it is not fooling since exergetic heat generation is small, 39 kW, thermoeconomic cost of heat results as 28.436 $/h.

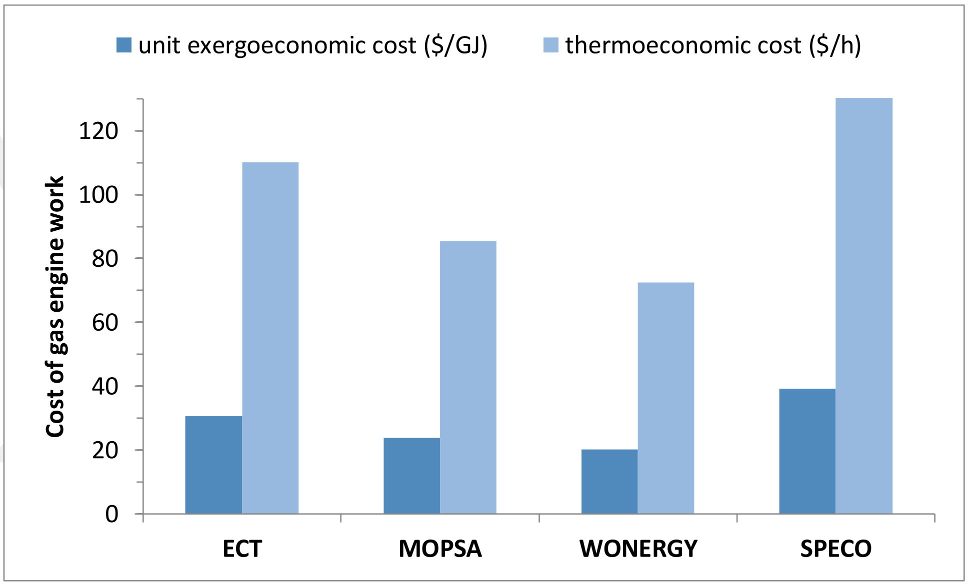


Figure 6.13 Comparison of the cost flows obtained for the work produced by the gas engine.

SPECO is the last cost analyzing method applied to the system. It explicitly defines the fuel and product application rules in Figure 4.3. Table 6.17 is created by using these rules it represents thermoeconomic cost balances and the corresponding auxiliary equations for each component in the system. Table 6.18 represents both unit exergoeconomic and thermoeconomic costs of flows. SPECO is the only method that gives the detailed cost of each stream other than the ECT. Cost flow tables given by both methodologies, Table 6.6 and Table 6.18, shows obviously that the most expensive flows belong to the luboil cycle. Thus, we understand that engine maintenance is very costly. Both fuel and product cost results for the components of the biogas engine powered cogeneration system according to the SPECO analysis are given in Table 6.19 and Table 6.20. The thermoeconomic cost accompanies of the work flow of the gas engine is 141 $/h. It is the highest value in Table 6.32 because SPECO don't perform detailed calculations and assumptions are permitted.

ECT is more detailed than the other theorems because it calculates the cost of each flow in subsystems. This detailed analysis does not ignore any cost incurred in subsystems, so it can be said that there is a superior viewpoint in ECT over other methods. As can be seen from the open literature, ECT has been applied to cogeneration systems in which different fuels are used [14,15, 22] and it has been observed that the thermoeconomic cost of the produced work varies markedly according to the complexity of the systems and the type of fuel used. On the other hand, although ECT evaluates the cost of the flows in the subsytems in a very detailed way it assumes the exergy destruction as another "product" in the system. Therefore, this method does not separate the actual production cost of a subsystem from the cost of its exergy destruction. Considering the other cost allocation methods, it should be noted that the MOPSA is a method that defines the cost of exergy destruction in a subsystem in the most understandable way. In the analysis of the CGAM system [53], it can be seen that MOPSA yields the highest work cost compared to other cost allocation methods. However, it is not the case in this study. This is partly due to the fact that the biogas engine powered cogeneration system in this study uses renewable fuel (biogas), as well as the system is more complex than the CGAM system for example, depending on the number of subsystems and the state of the flows.

Although it is a relatively new method, it can be said that the Wonergy is one of the most useful methods that can be easily applied to a cogeneration system. This method does not calculate the costs separately for each flow in the subsystems as the ECT method does, or it does not explicitly calculate the exergy destruction costs of the subsystems as in the MOPSA method. However, it separately calculates the costs of work and heat generated in a cogeneration system, and in a sense, Wonergy method reveals the purpose of the cogeneration system in a holistic manner.

The SPECO method can make very flexible assumptions among the other methods we have evaluated above, thus making it easier to apply to a cogeneration system. This method does not perform a detailed analysis such as ECT, nor does it calculate the costs of the exergy destructions of the subsystems like MOPSA nor does the direct cost analyses of work and heat which are the main outputs of the cogeneration system like Wonergy. Due to this structure of the method, SPECO is the method that calculated the highest costs in this study.

At the end of the comments, naturally attentions are directed towards the cost of the work produced by the gas engine since it is the most important parameter obtained by the thermoeconomic analyzing methods to achieve the maximum profit. All gas engine work cost values obtained from cost accounting analyzes are compared in Figure 6.13.

6.6 Discussions and Comparision of Optimization Results

To optimize our system two methods are choosen. The first of thermoeconomic optimization methods is TFA, a design optimization method. It aims to calculate the optimum costs based on the relations between the products and the units in which they are produced. The pressure ratio of the compressor, r_C , exergetic efficiency of the compressor, ε_C , exergetic efficiency of the turbine, ε_T , and the temperature of the exhaust gases entering the turbine, T_{23} , are determined as optimization variables. This method eveluated the system components which mainly take part in work production as units. Therefore pumps, HE1, HE2, LOHE are eliminated and a new adopted system is modeled as Figure 6.2. It is obvious that, TFA only regards with the gas line. An adopted system is used since TFA allows to write exergetic function for each unit product over the mass flow rate of air and gas in the process starting at the compressor and ending at the EGHE.

Functional analysis requests a functional diagram which establishes the relations of the unit functions hence a functional diagram illustrating the adopted system in detail is drawn as Figure 6.3 for TFA. However, two types of new units are seen at this figure; a junction and two branching points. These units are completely virtual and added to understand optimization process in more detail. After drawing the functional diagram, the objective function defining the system for optimization is written. Considering that the Lagrange multiplier method is appropriate for the solution of such optimization problems, it is also choosen for TFA.

The adopted system is modeled thermodynamically, as in Table 6.25, and economically, as in Equation 6.29. The cost functions for each unit are written and the constants used in the functions are clearly specified because this is important for calculations. In addition, the equations describing the product of each unit and its relationship with other units are formulated. These equations are also equality constraints for the objective function and also inequality constraints are set. The applications of Lagrange multipliers to the system is the last step in explaining TFA. Final results of the cost optimization is represented in Table 6.29. The Lagrange multiplier for the gas engine work is detected as 26.86 $/GJ.

Second thermoeconomic optimization method implemented on the adopted system is EFA. It is used for both design and operation optimization. Analyzes start with defining the thermoeconomic structure of EFA. In relation to this process system products, unit inputs, junctions, branches, and physical limits are identified. This theorem gives particular importance to the concept of internal economy, so the junctions and branch points are explained in detail. Each unit's product and fuel definitions are made individually. The required functional diagram for EFA is given.

The primary unit costs at the optimum point for adopted system according to EFA are calculated. During calculations Lagrange multiplier method is used again. Lagrange method makes processes easier since there are a lot of equality contraints in both optimization methods. EFA calculates the Lagrange multiplier for the gas engine work as 24.403 $/GJ. Furthermore the remaining unit costs at the optimum points are represented.

While TFA is the design optimization method, it can be said that it is doing both design and operation optimization for EFA. This is why EFA has examined the system in more detailed and more rigorous manner than TFA. This situation can also be understood from the functional diagram drawn by them. In TFA, only one junction and two branching points are used, while EFA is used for each unit either junction or branching point, or both. Furthermore, EFA examines the system within the framework of four different exergetic flows; mechanical exergy loop, thermal exergy loop, power exergy loop and negentropy loop. The internal economy was developed while the thermoeconomic structure is being created and this process brings a different perspective to optimum cost analysis. Another difference between the two methods is; while TFA considers the same Lagrange multiplier as all flows into a unit, EFA approves each flow with a distinct Lagrange multiplier entering a unit. The struggle against entropy production is evaluated as a separate cost, so unit product costs decreased compared to TFA. Figure 6.14 compares the optimization cost results for the units in the adopted BPCS.

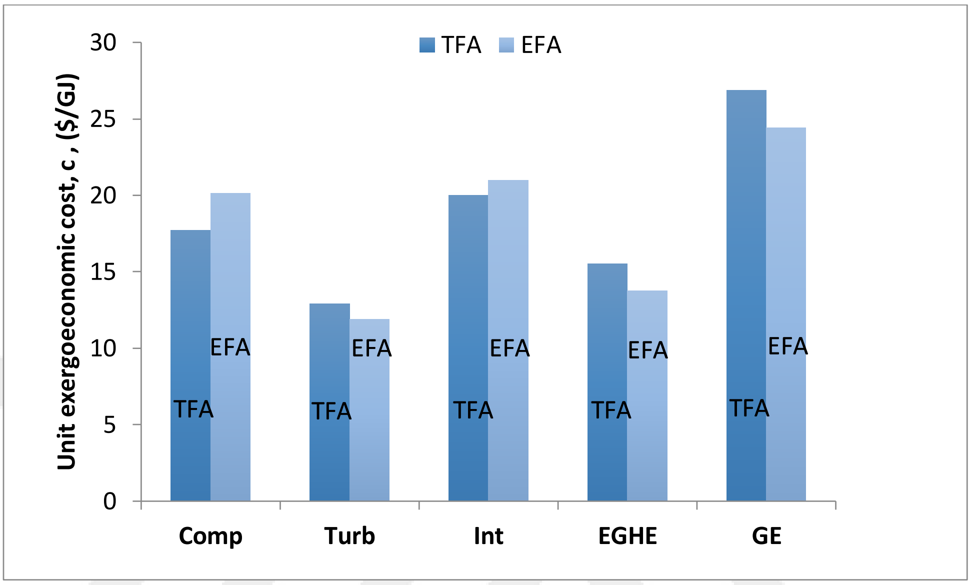


Figure 6.14 Comparison of the costs for the units in the adopted system obtained from optimization methods, TFA and EFA.

Both optimization results showed that work production from gas engine is the most expensive function in the system. It is obvious from Table 6.31, although same approach is used to reach the costs of major unit products, results are different obtained from TFA. Most values of Table 6.31 are smaller than the ones in Table 6.29. This indicates the importance of internal economy in EFA. Because a part of the cost was loaded to negentropy.

During optimization process, especially on a system that is already running like ours' it is necessary to think why we didn't get the same results from cost accounting. Furthermore the calculated values for the desicion variables are selected from Table 4.1. The answer is actually hidden in Equations from (6.52) to (6.57) for TFA and Equations from (6.106) to (6.110) because to reach the Lagrange multipliers these equartions are derived several times with respect to the selection variables which results with optimum values. By this way, although TFA is a design optimization method, we perform both design and operation optimization as in EFA.

6.7 Conclusions

Cost accounting analyzing methods which developed in chapter 4 are implemented on the biogas fuelled cogeneration system. Each method gives different cost results due to their different mathematical foundations. These differences are compared and discussed explicitly.

Two optimization methods presented in chapter 5 are implemented on the cogeneration system Both methods use Lagrange multipliers approach. The Lagrange method is a convenient and useful method for detailed optimization procedures. The results are discussed and comments on optimization procedure are presented.

CHAPTER 7

CONCLUSIONS

In this thesis, the comprehensive thermoeconomic analysis and optimization approaches were applied to an existing biogas fuelled and internal combustion engine powered cogeneration system located in Gaziantep (Gaski Biogas Engine Powered Cogeneration System) with an electrical power output of 1000 kW and a hot water massflow rate of 20.9 kg/s. The analyzes and results obtained within the scope of this thesis directed us to the following conclusions:

1. Four cost accounting methodologies, based on exergy and economy, are implemented on an existing biogas engine powered cogeneration system. Fuel-product definitions for each component which make up the system are performed and represented in Table 4.2. The exergy balance for each component of the cogeneration system is formed. It is pointed out that product exergy should be smaller than the fuel exergy for every component.

2. Exergetic efficiencies of components are; compressor 67.43% , turbine 87.726%, intercooler 47.7%, EGHE 37.87%, HE1 57%, HE2 54.2%, LOHE 52.49%, P1 90.9%, P2 68.86%, P3 88.65%, P4 28.36%, GE 24.7 %. The total efficiency of the system is calculated as 26.4% by considering both work and heat production. The highest exergy destruction occurs in the biogas engine due to the unavoidable heat transfer from the engine system to the room environment.

3. The operating and maintenance costs are obtained by considering our cogeneration system's entire economic life which is 25 years; from 2006 to 2031. These costs are escalated by using average nominal escalation rate, which is 5% in US dollars. The system operates at full load 8030 h out of the total available 8760 h per year. The total capital investment for this system is 1.237 million US dollars. All equipment costs related with the system are given in Table 6.5. Unit cost of the produced biogas is taken as 6.35 $/GJ. After detecting the installation and maintenance costs of the system components, each method has written a thermoeconomic cost balance from its own point of view; ECT as Equation (4.25), MOPSA as Equation (4.29), Wonergy as Equation (4.37) and SPECO as Equation (4.52).

4. The first one of the four cost analysis methods applied on the system is ECT. It brought a very useful concept to thermoeconomics; exergetic cost. The exergetic costs of the flows are obtained with the help of the incidence matrix and indicated in Table 4.6. Unit exergetic cost, κ^*, which is the ratio of the exergetic cost to exergy gives clues about the amount of exergetic consumption. It can be concluded that it is more expensive to obtain exergetic flows having higher unit exergetic costs, which is why Table 4.6 is important in this sense. This concept requires to make a detailed analysis. Unit exergoeconomic costs are determined from the thermodynamics and economic relationship. Equations in the cost hexagon in Figure 4.3 clearly reveal this relationship thus unit exergoeconomic costs of flows obtained as a result of solving these equations are shown in Table 6.1. Finally, thermoeconomic costs of products and fuels for all componets according to ECT are shown in Table 6.7 and Table 6.8 respectively. ECT results in a thermoeconomic cost for the gas engine work of 110.065 $/h shown in Table 6.4.

5. MOPSA has a different perspective on the exergetic flows circulating in the system. It specifies a unit exergy cost for every decomposed exergy stream. c_T, c_M notations are attributed as the unit exergoeconomic costs according to thermal and mechanical exergies for gas streams and d_T, d_M are attributed for the water. We assign d_T and d_M also for lubrication oil streams since they are liquid. After signification the flows in the thermal and mechanical parts in Table 6.10, the exergetic balance for each component is identified in Table 6.11. During the calculations, the most difficulties ocur in the heat exchangers; intercooler and EGHE where two different kind of fluid passes. Table 6.13 gives the thermoeconomic cost of work as 85.536 $/h for the gas engine, essentially this table indicates that MOPSA gives particular importance to negentropy, and the fact that this irregularity has a separate cost. Since the obtained value is smaller than the found ECT.

6. Wonergy is the combination of the energy and exergy flows in a power plant. There are different Wonergy assumptions depending on differences which are accepted. The methodology considered in this study, accepts the exergy as Wonergy, furthermore, components making up the system are classified by their tasks. The general cost balance equation for the Wonergy theory is written to include a wonergetic unit cost, c_k . This wonergetic cost balance equation is seperated into three parts according to the unit classifications. A careful analysis makes clear that, the level of Wonergy input, $\dot{K}$, plays the most important role in determining the costs. The calculated thermoeconomic cost of work produced from the gas engine is 72.5 $/h. It is the smallest value of the comparison values in Figure 6.13. This result focuses on work production because the Wonergy method attributes responsibility not just to the gas engine, but also to it being shared among other components.

7. Finally, SPECO is implemented on the system. It also clearly defines the fuel and product application rules, which are the basis for calculating the costs. These rules suggest auxiliary equations to make calculations easier. Table 6.17 represents thermoeconomic cost balances and the corresponding auxiliary equations for each component in the system. Both fuel and product cost results for the components of the biogas engine powered cogeneration system according to the SPECO analysis are pointed out in Table 6.19 and Table 6.20. The thermoeconomic cost devoted for the work flow of the gas engine is 141 $/h. It seems the biggest value in Figure 6.13 due to flexible assumptions of this method.

8. Two thermoeconomic optimization methods are applied on this system. In both methods, the pressure ratio of the compressor, r_C , exergetic efficiency of the compressor, ε_C , exergetic efficiency of the turbine, ε_T , and the temperature of the exhaust gases entering the turbine, T_{23} , are determined as optimization variables. As a matter of fact, our system is already existing and the production of the work is considered as fixed.

9. The first of thermoeconomic optimization methods is TFA, a design optimization method. It calls the products of the units as functions. TFA restricted the biogas powered cogeneration system to the units which are on the gas line only, hence system is remodelled. An adopted system is drawn as Figure 6.2 since TFA allows to write exergetic function for each unit product over the mass flow rate of air and gas in the process starting at the compressor and ending at the EGHE. Functional analysis needs a functional diagram which establishes the relations of the unit functions. New units are defined; junction and branch, and represented in Figure 5.2. These units are completely virtual and added to understand optimization process in more detail. Hence a functional diagram illustrating the adopted system in detail is drawn as Figure 6.3 for TFA. A junction and two branching points are added to the real units. After the functional diagram is represented, the objective function defining the system for optimization is written as Equation 6.50 with its desicion variables. Lagrange multiplier method is selected to solve the equations.

10. EFA is the second thermoeconomic optimization method implemented on the adopted system. It performs both design and operation optimization. EFA firstly gives the information to built thermoeconomic structure. System products, unit inputs, junctions, branches, and physical limits are clarified. Figure 6.10 and 6.11 emphasize the local applications of junctions and branches. Functional diagram of the system for EFA is represented in Figure 6.12. Thermoeconomic model of the adopted cogeneration according to EFA is illustrated in detail by a long formulation series, from Equation 6.58 to Equation 6.104. Physical limits, inequality contraints, for EFA is given by Equation 6.105. The inputs, outputs, and junctions, branching points of the units that make up the system are explained in this series of equations. However, entropy generation due to gas engine can not be calculated with the original formula of the methodology, in this situation it is determined based on the entropy production caused by other units. This allowed us to make more sensible calculations.

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Derya HAYDARGİL, Ayşegül ABUŞOĞLU. (2018). A Comparative Thermoeconomic Cost Accounting Analysis and Evaluation of Biogas Engine-Powered Cogeneration. Energy,159, 97-114.

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